LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Horizontal Access Module (HAM) - Seismic Attenuation System (SAS):
HAM-SAS System Dynamics Model

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LIGO Science Collaboration

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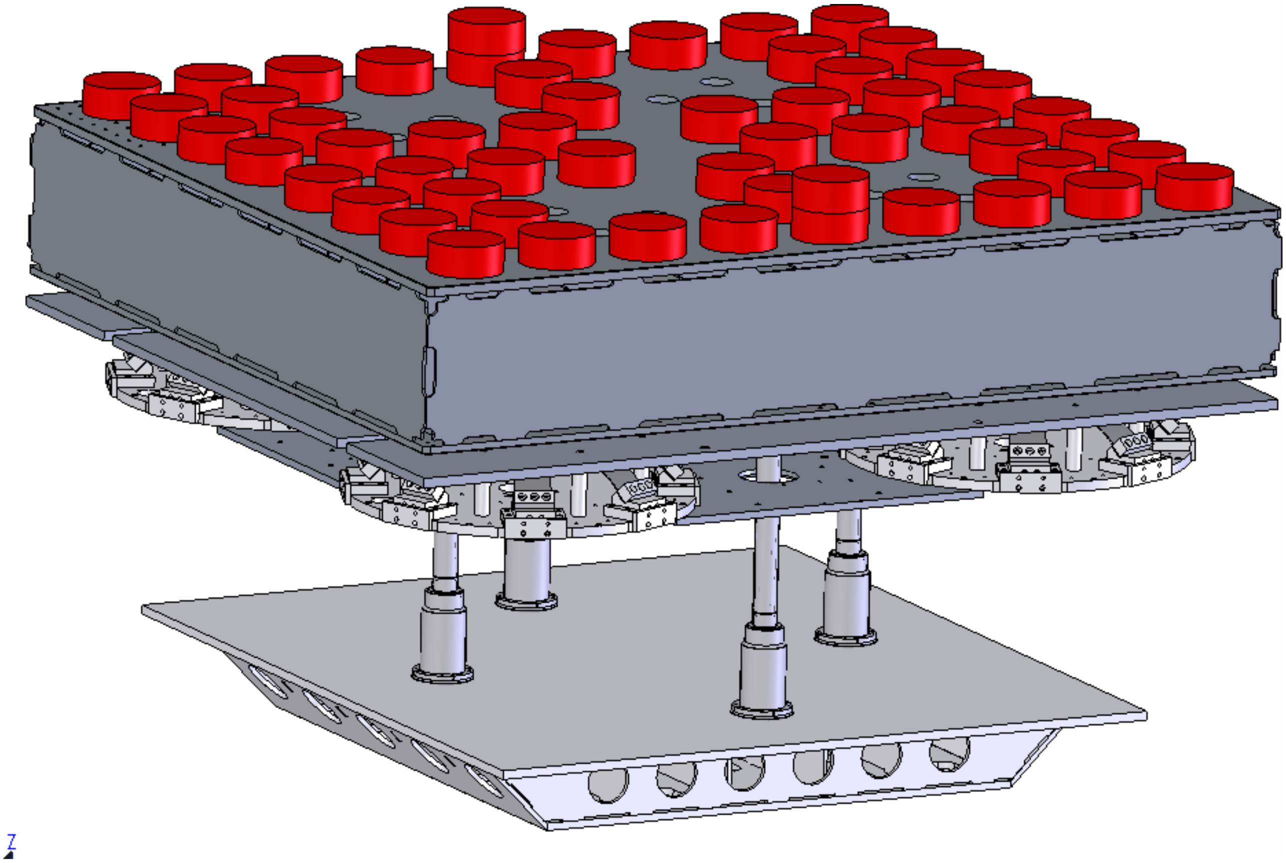
1 Introduction

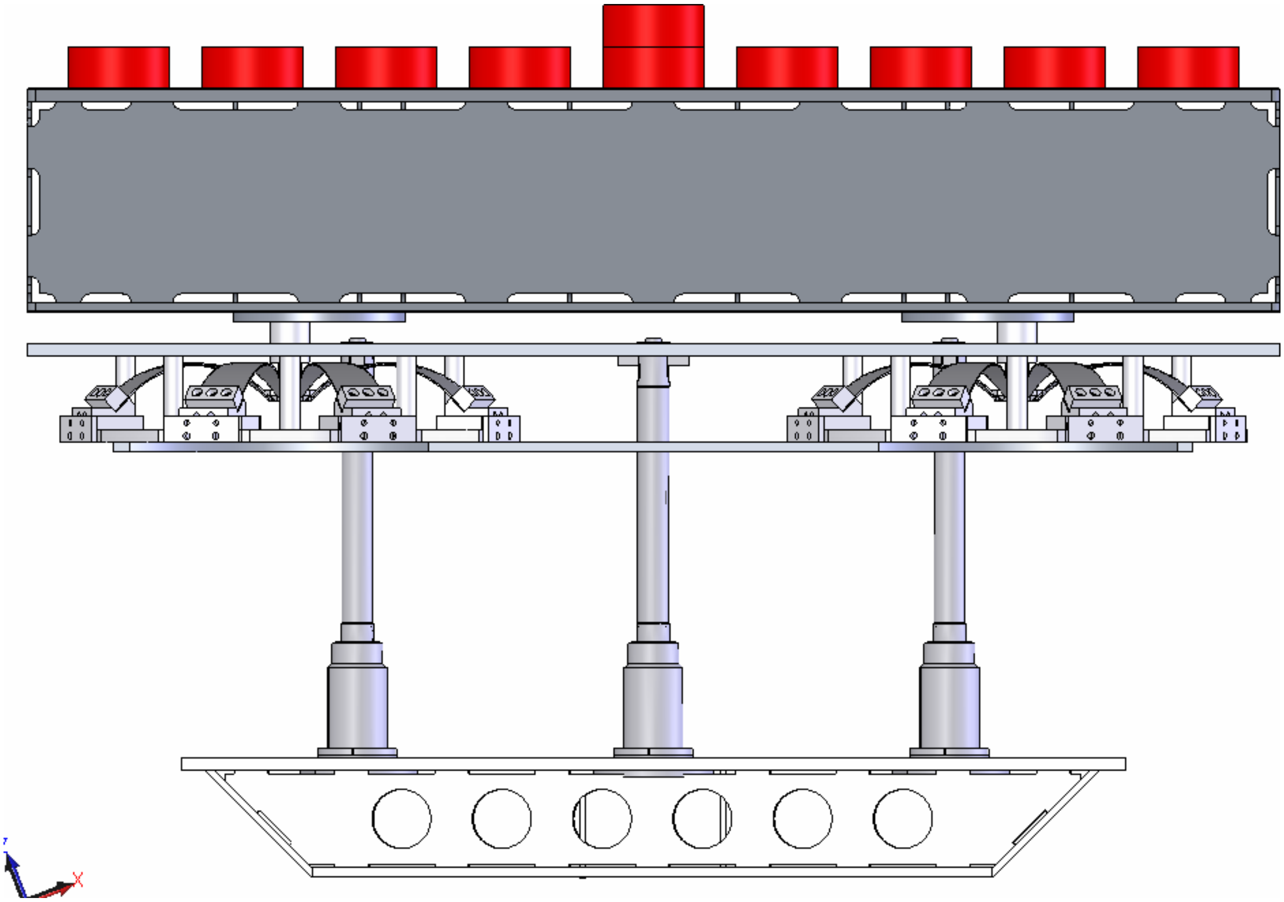
A Seismic Attenuation System (SAS) design has been proposed for use in the Horizontal Axis Module (HAM) vacuum chamber. A three-dimensional, multi-degree of freedom, dynamics model of the structural plant has been developed to aid in evaluating the HAM-SAS design and to help in developing servo-controls.

2 SAS Overall Assembly

The SAS overall assembly (Figure 1) consists basically of 4 Inverted Pendulums (IP) supporting a Spring Box assembly with 4 Geometric Anti-Spring (GAS) filter modules. The GAS filter assemblies in turn support an Optics Table (OT). The IPs are attached at their lower ends to a support platform (similar to the initial LIGO HAM seismic isolation system) which is attached to two support tubes which penetrate the vacuum chamber with bellows.

Figure 1: HAM-SAS Assembly
Only the structural elements are shown. Actuators, LVDTs and associated bracketry are not shown.




Y
X

3 Component Analysis

3.1 Spring Box Assembly

Figure 2: Spring Box Assembly

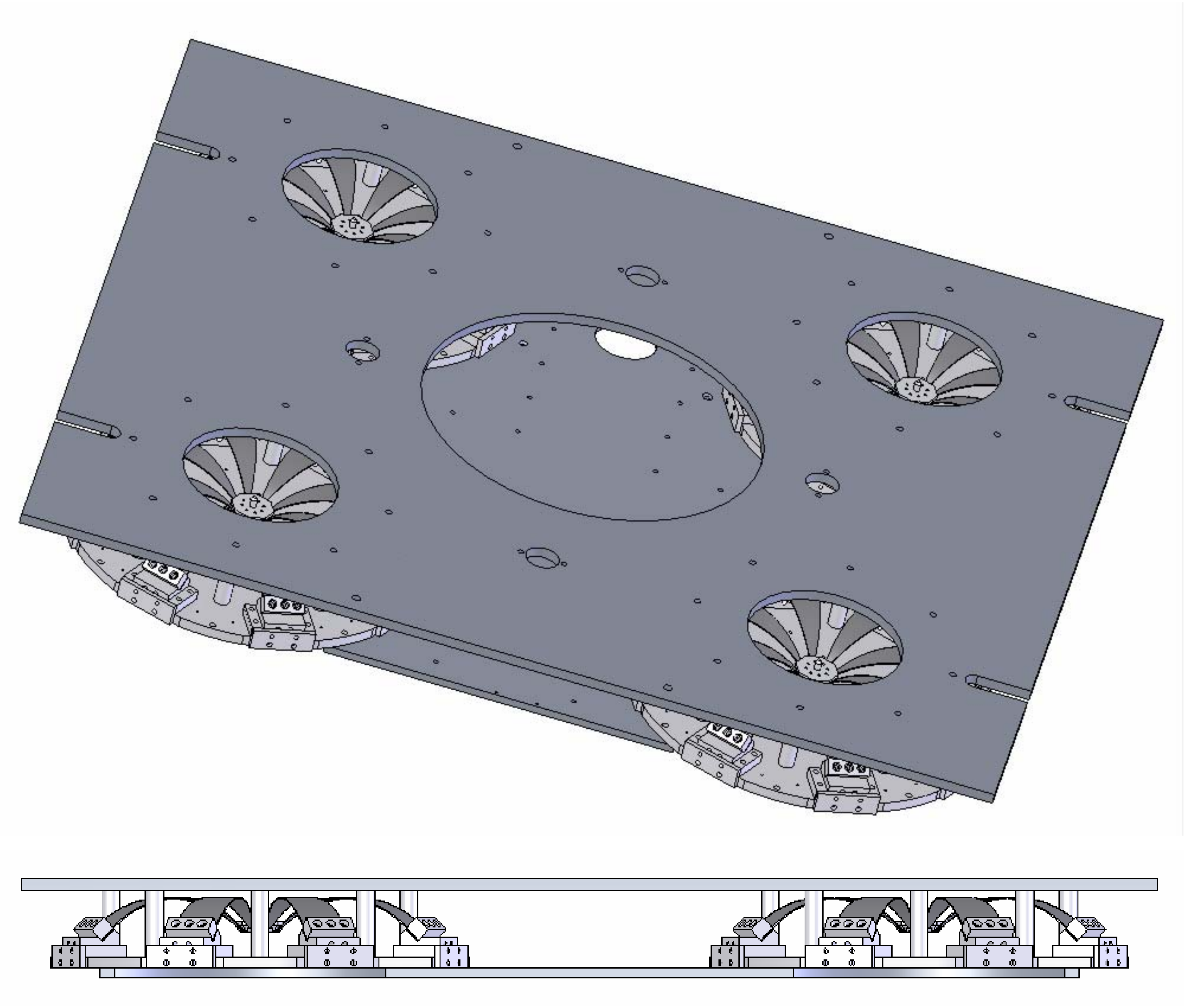
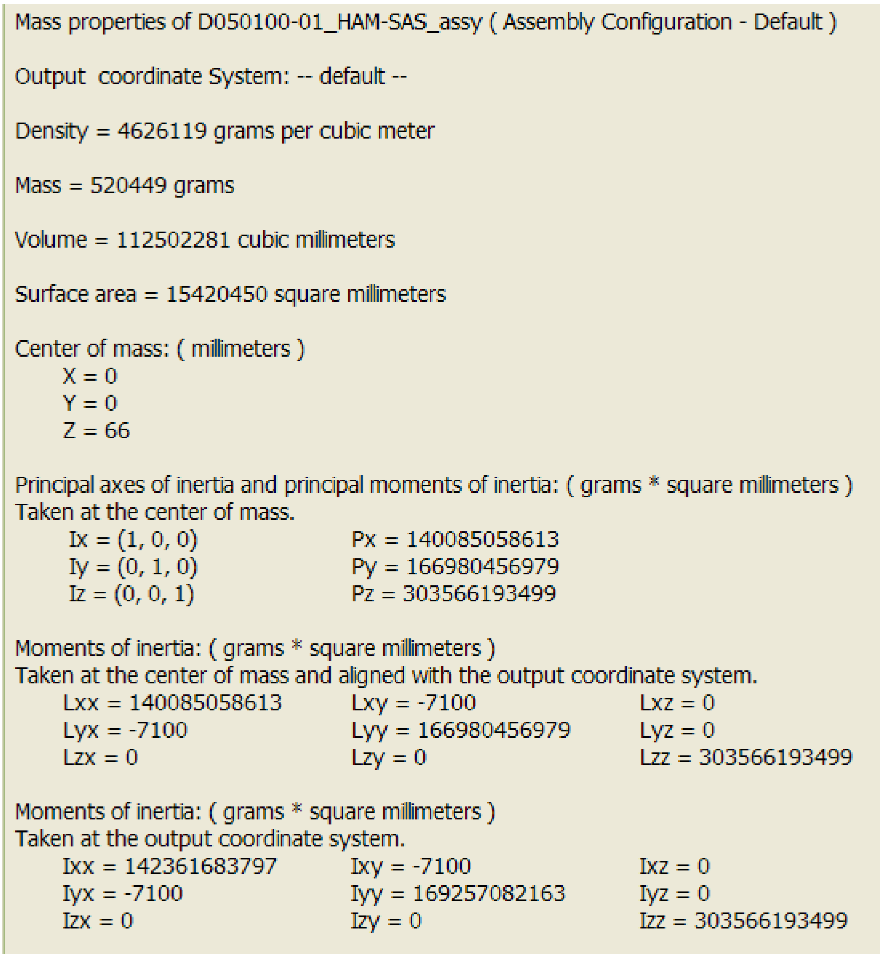


Figure 3: Mass Properties of the Spring-Box Assembly



```
Mass properties of D050100-01_HAM-SAS_assy ( Assembly Configuration - Default )

Output  coordinate System: -- default --

Density = 4626119 grams per cubic meter

Mass = 520449 grams

Volume = 112502281 cubic millimeters

Surface area = 15420450 square millimeters

Center of mass: ( millimeters )
      X = 0
      Y = 0
      Z = 66

Principal axes of inertia and principal moments of inertia: ( grams * square millimeters )
Taken at the center of mass.
       Ix = (1, 0, 0)                  Px = 140085058613
       Iy = (0, 1, 0)                  Py = 166980456979
       Iz = (0, 0, 1)                  Pz = 303566193499

Moments of inertia: ( grams * square millimeters )
Taken at the center of mass and aligned with the output coordinate system.
      Lxx = 140085058613        Lxy = -7100                 Lxz = 0
      Lyx = -7100               Lyy = 166980456979          Lyz = 0
      Lzx = 0                   Lzy = 0                     Lzz = 303566193499

Moments of inertia: ( grams * square millimeters )
Taken at the output coordinate system.
      Ixx = 142361683797        Ixy = -7100                 Ixz = 0
      Iyx = -7100               Iyy = 169257082163          Iyz = 0
      Izx = 0                   Izy = 0                     Izz = 303566193499
```

The origin is at the center of the lower surface of the lower plate.

3.2 Optics Table & Payloads

For expediency, rather than use the new SAS design for the Optics Table, I used the existing Optics Table. The stiffness and mass properties are similar. There is also potentially significant savings if the existing tables can be re-used or adapted for SAS use.

3.2.1 Low payload C.G. Configuration

The HAM optics table payload compliment varies in type and position. However the total mass is intended to always be the same, 510 kg (per E040136). For the purpose of approximating the payload mass moment of inertia matrix, the payload mass is represented by stainless steel weights (same as used in initial LIGO) arrayed evenly across the optics table. In this analysis the optics table is assumed to be rigid.

Figure 4: Optics Table and Payload

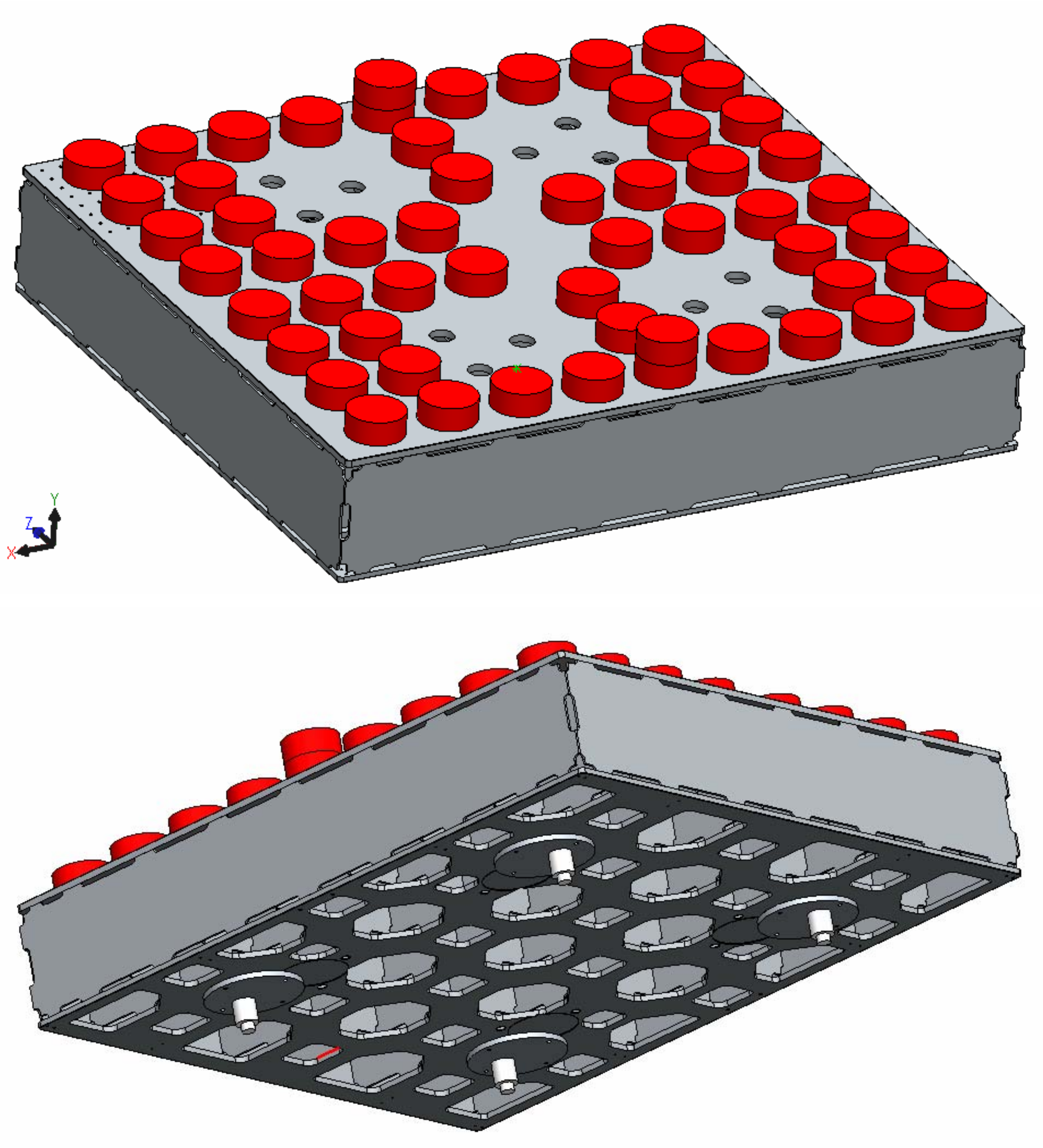
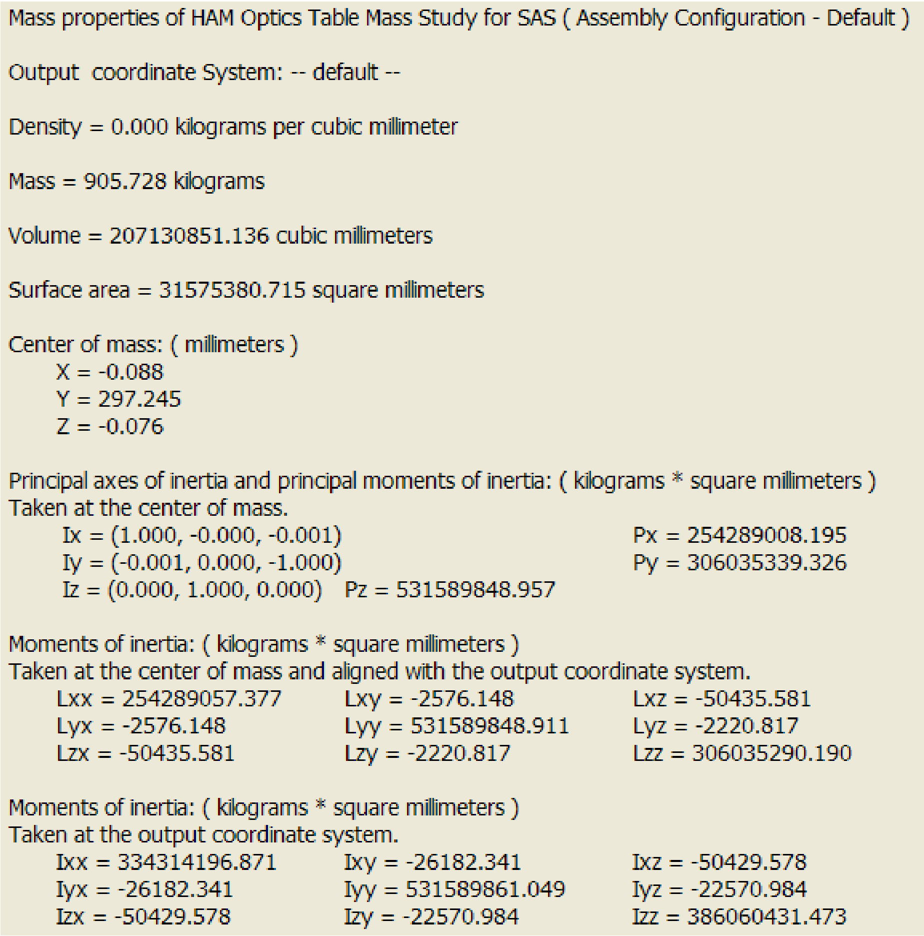


Figure 5: Mass Properties of the Optics Table and Payload



```
Mass properties of HAM Optics Table Mass Study for SAS ( Assembly Configuration - Default )

Output  coordinate System: -- default --

Density = 0.000 kilograms per cubic millimeter

Mass = 905.728 kilograms

Volume = 207130851.136 cubic millimeters

Surface area = 31575380.715 square millimeters

Center of mass: ( millimeters )
      X = -0.088
      Y = 297.245
      Z = -0.076

Principal axes of inertia and principal moments of inertia: ( kilograms * square millimeters )
Taken at the center of mass.
       Ix = (1.000, -0.000, -0.001)                      Px = 254289008.195
       Iy = (-0.001, 0.000, -1.000)                      Py = 306035339.326
       Iz = (0.000, 1.000, 0.000)   Pz = 531589848.957

Moments of inertia: ( kilograms * square millimeters )
Taken at the center of mass and aligned with the output coordinate system.
      Lxx = 254289057.377       Lxy = -2576.148            Lxz = -50435.581
      Lyx = -2576.148           Lyy = 531589848.911        Lyz = -2220.817
      Lzx = -50435.581          Lzy = -2220.817            Lzz = 306035290.190

Moments of inertia: ( kilograms * square millimeters )
Taken at the output coordinate system.
      Ixx = 334314196.871       Ixy = -26182.341           Ixz = -50429.578
      Iyx = -26182.341          Iyy = 531589861.049        Iyz = -22570.984
      Izx = -50429.578          Izy = -22570.984           Izz = 386060431.473
```

The coordinate origin for the optics table & payload mass assembly is the center of the lower surface, with +Y up.

3.2.2 High payload C.G. Configuration

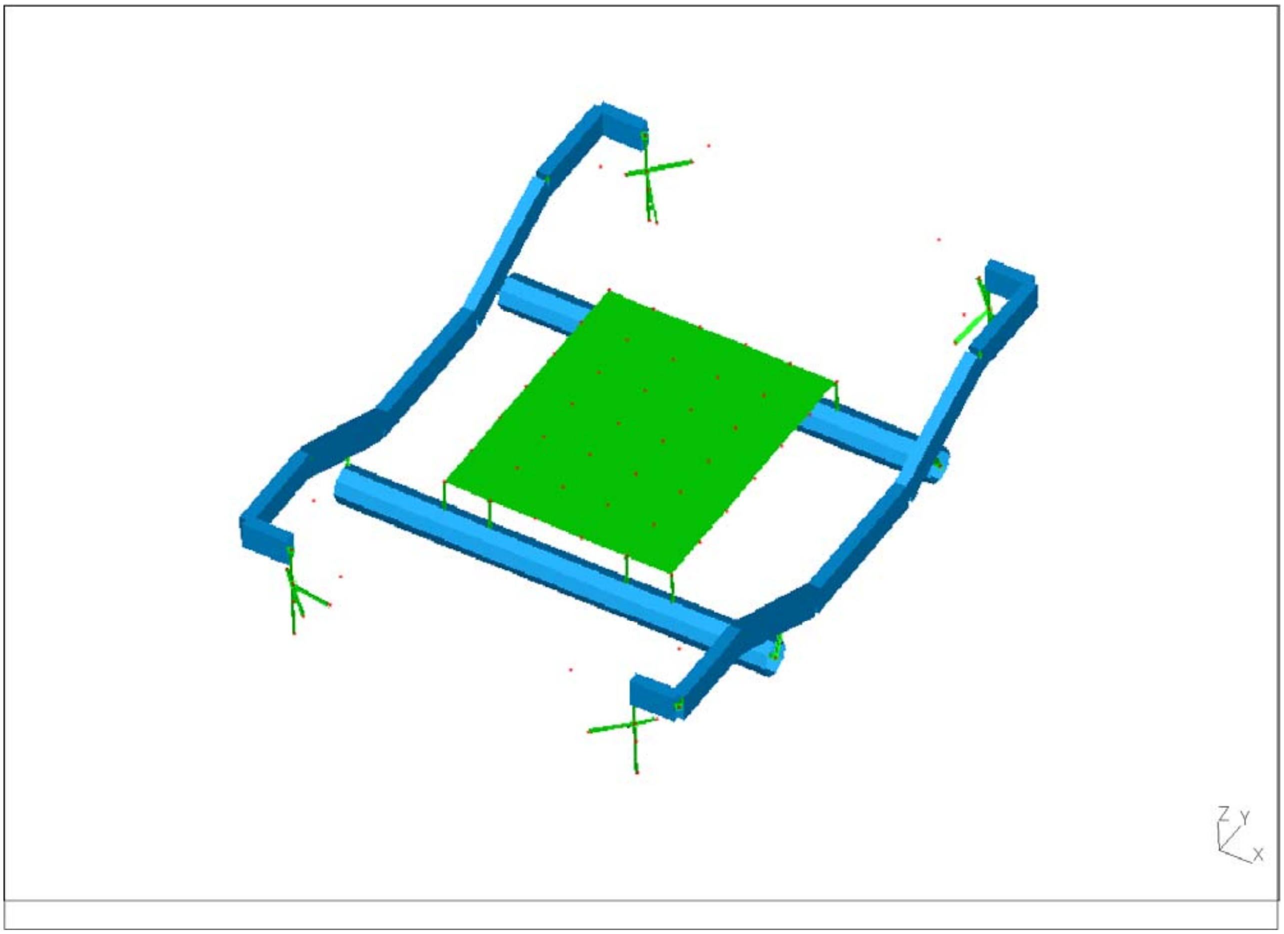
TBD

3.3 Support Structure Assembly

The following model of the support structure assumes an initial LIGO Coarse Actuation System (CAS) supporting the crossbeams on each of the 4 piers (as opposed to a set of 4 HEPI actuator assemblies).

N.B.: The support structure model has not yet been married to the SAS model.

TBD: INSERT MODEL INFO FROM I-DEAS



3.3.1 Support Table Stiffness

Since a model of the initial LIGO support table existed and it is likely similar in stiffness to the HAM-SAS support table, this model is used in developing the support structure assembly model. The effective stiffness of the simple plate representation of the support table has been based on the static compliance to a uniform surface load as calculated with the detailed finite element model of the support table.

Figure 6: Support Structure FEM

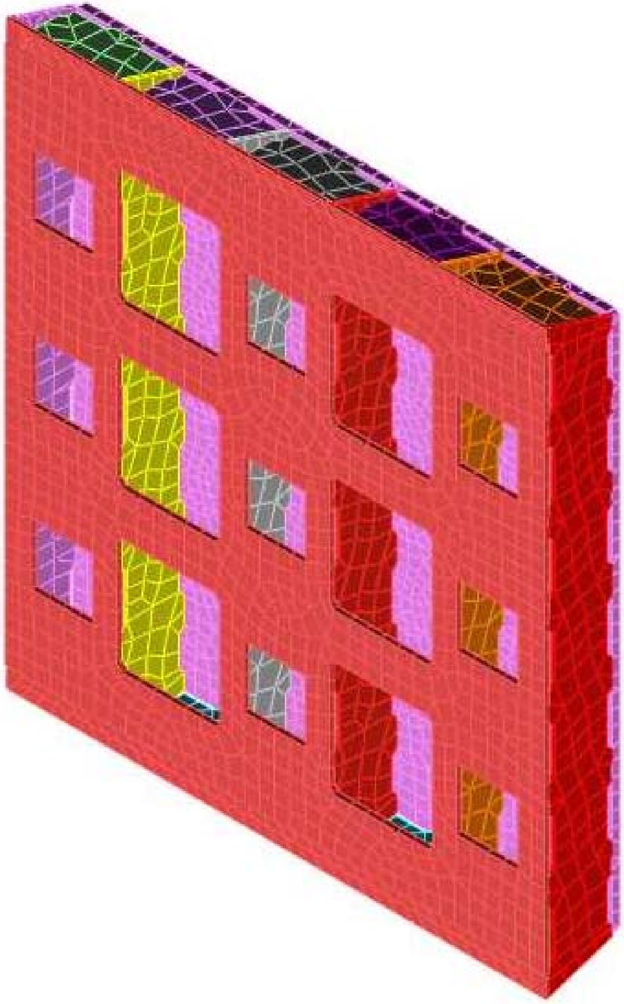
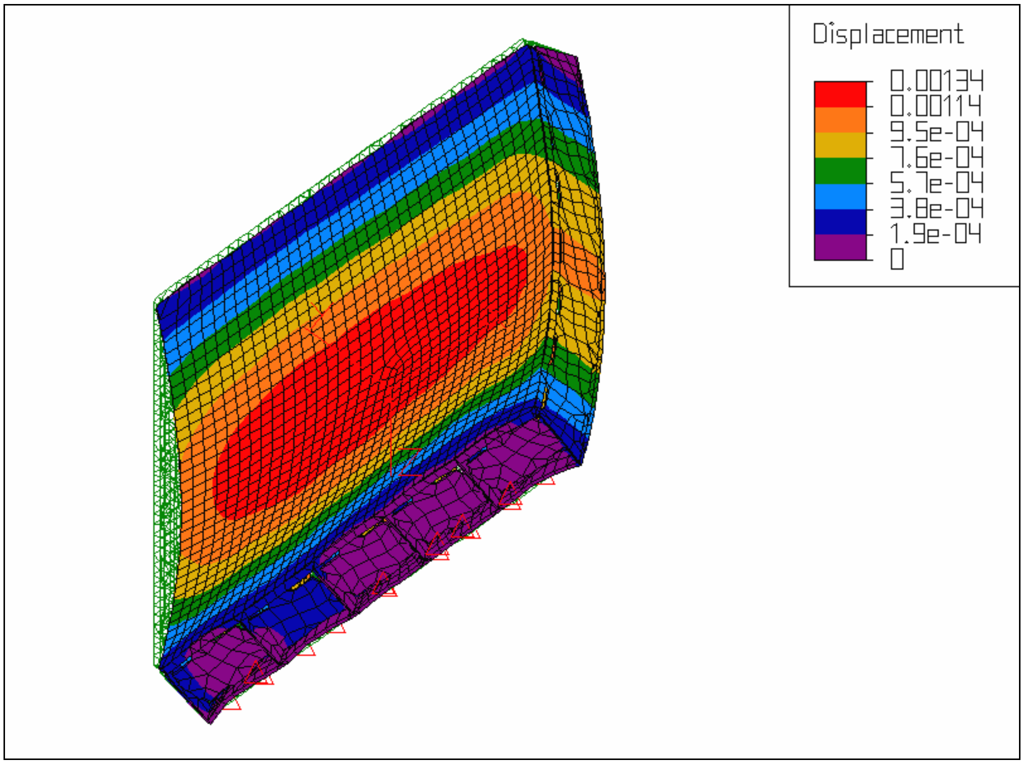


Figure 7: Support Structure Displacement for uniform surface load



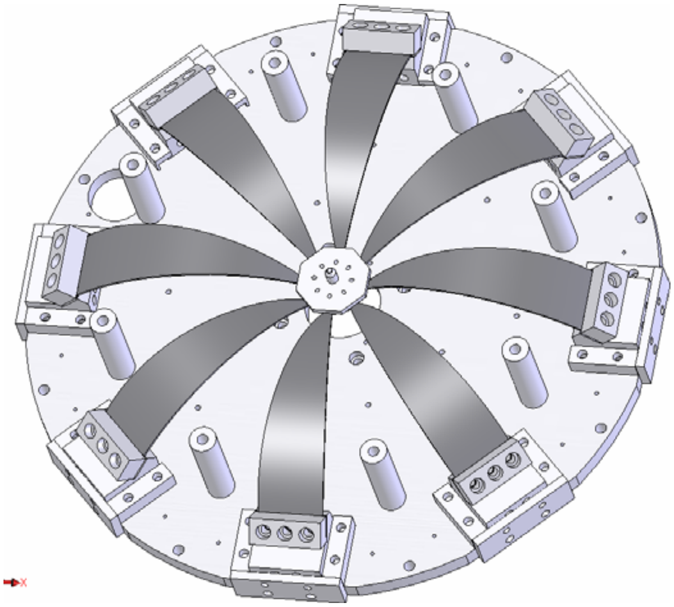
Balance of description TBD

3.4 GAS Filter Blade Stiffness

In principle, the Geometric Anti-Spring (GAS) Filter assembly (D050106), depicted in Figure 6, can consist of 2, 4 or 8 spring blades. Each blade (D050120) can in turn be ¼, ½ or full width. In the analysis presented here 8 full width blades are assumed to carry the full intended payload mass.

The load on the GAS Filter springs consists of the payload mass plus the optics table mass. As indicated in section ?, the total load on the 4 GAS filters is 906 kg. Consequently the load on a single GAS Filter blade is 906 x 9.8/32 = 277 N.

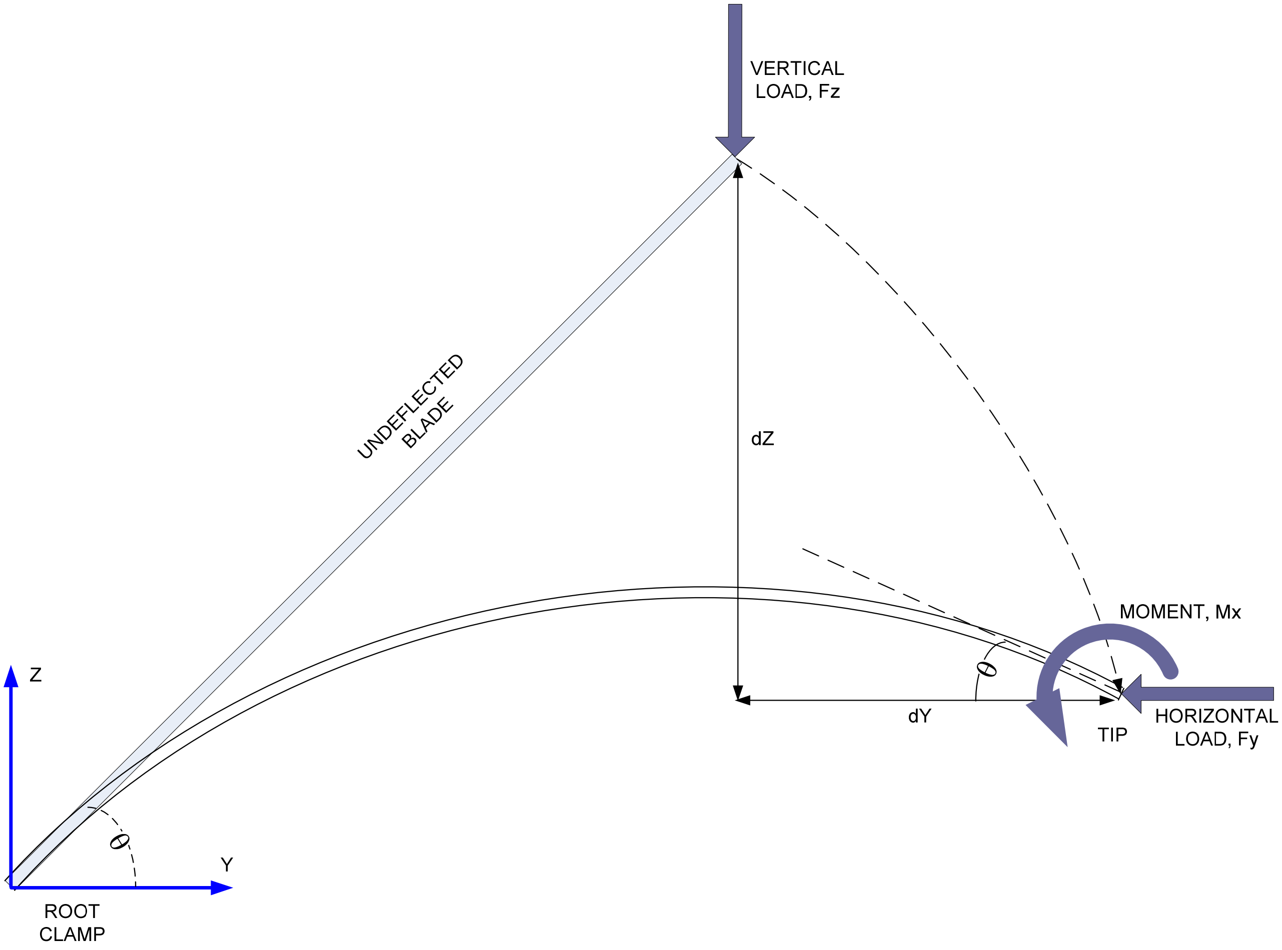
Figure 8: GAS Filter Assembly



3.4.1 Large Deflection, Static Analysis

The full width blade (D050120) has a shaped planform, but is essentially trapezoidal. In the analysis that follows, the blade is assumed to be a trapezoid, with a length between clamps of 273 mm, a root width of 72 mm, a tip width of 10 mm and a uniform thickness of 2.15 mm. In this analysis we assume a constant vertical tip load, but allow for a varying root clamp to tip clamp horizontal width. The spring blade root clamp can be adjusted radially on the GAS filter base plate to adjust the horizontal root to tip distance. In addition we need a mechanism to adjust the vertical working position. In the HAM-SAS system this is accomplished with the vertical stepper motor/coil-spring assembly.

Figure 9: Blade Spring Geometry



3.4.1.1 Tip Clamp Angle Tuning

In the SAS design the tip angle is set by machining the tip clamp. One can choose this angle as part of the approach to getting the blade spring to act as an anti-spring, rather than (or in addition to) adjusting the vertical tuning force. If the vertical force is left equal to the static load and a tip moment is applied to effect a change in tip rotation as well as vertical position, then one can map out the tuning curves (tip horizontal and vertical position relative to the flat blade) shown in Figure 10. The vertical resonant frequency tuning results were obtained by a geometrically nonlinear, shell finite element model using ANSYS. Note that near the bifurcation point, there is extreme sensitivity to the horizontal position. Hence the need for active servo feedback to keep the blade tip position at its tuning point. If tuning to ~30 mHz, it appears from this analysis that the horizontal position of the tip must be maintained to ~0.2 mm. For this tuning solution, the tip angle is ~5 deg from horizontal. The GAS filter blade central support (D050124) is designed for a 33 deg tip angle.

Figure 10: Spring Blade Tuning with Mx and Fy

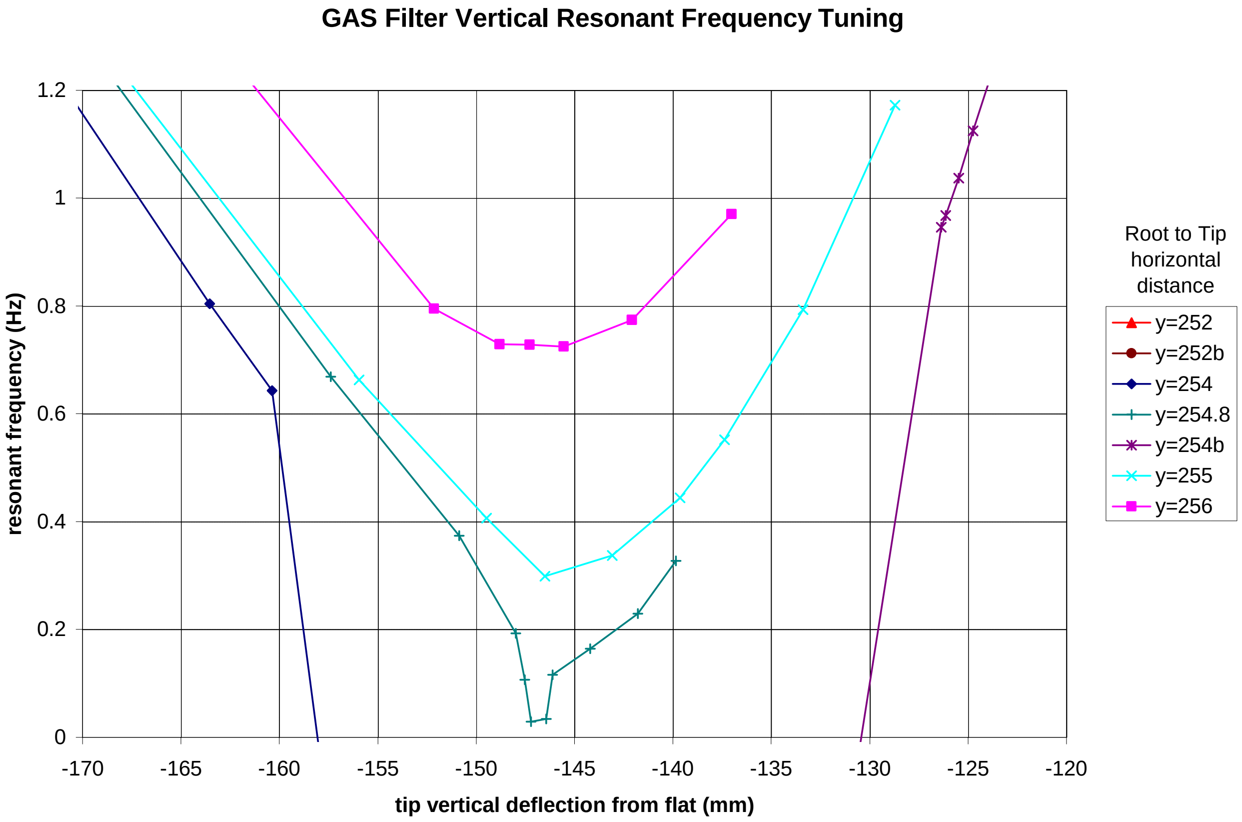
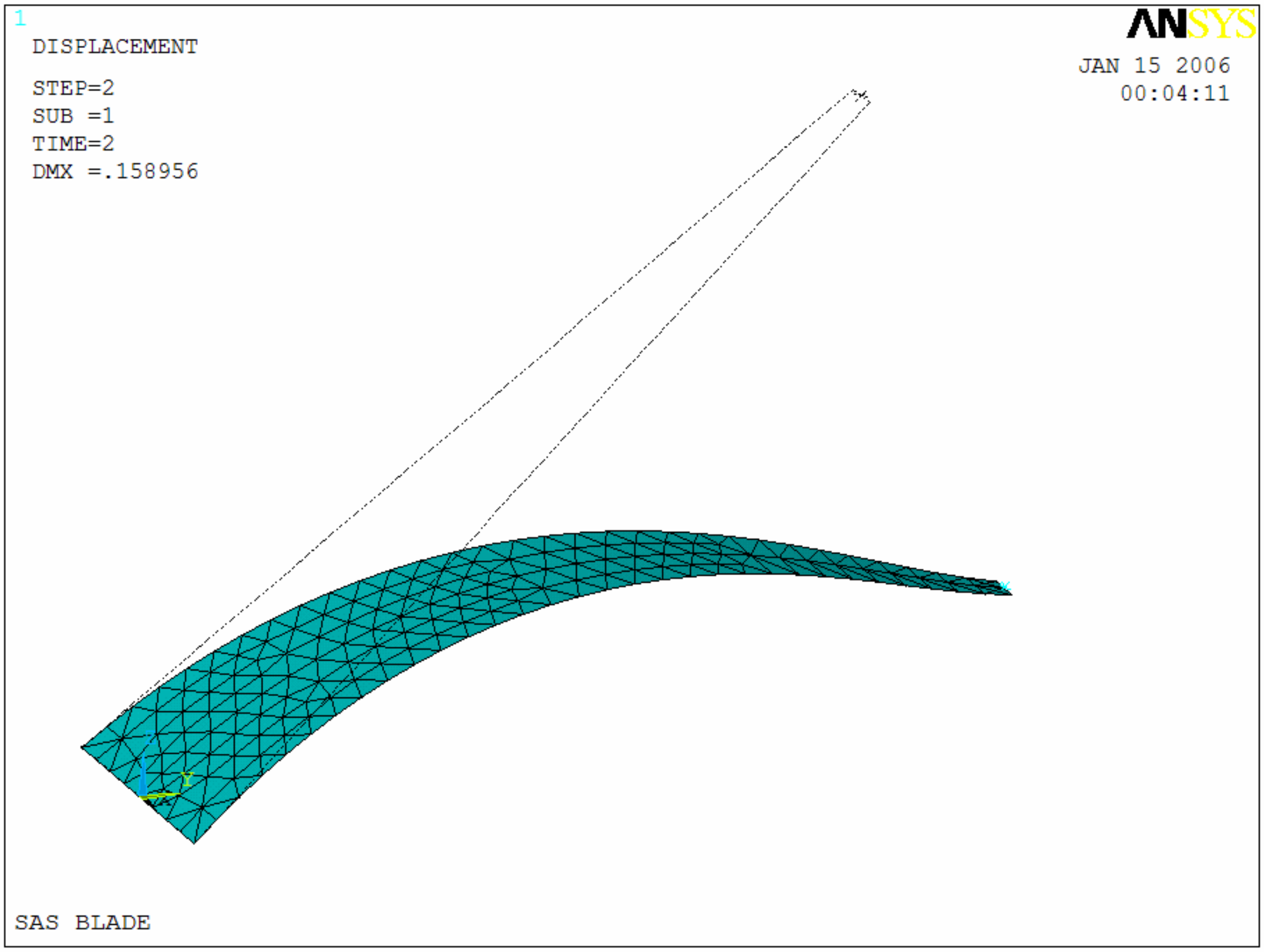


Figure 11: Deformed Blade Shape at the tuned position



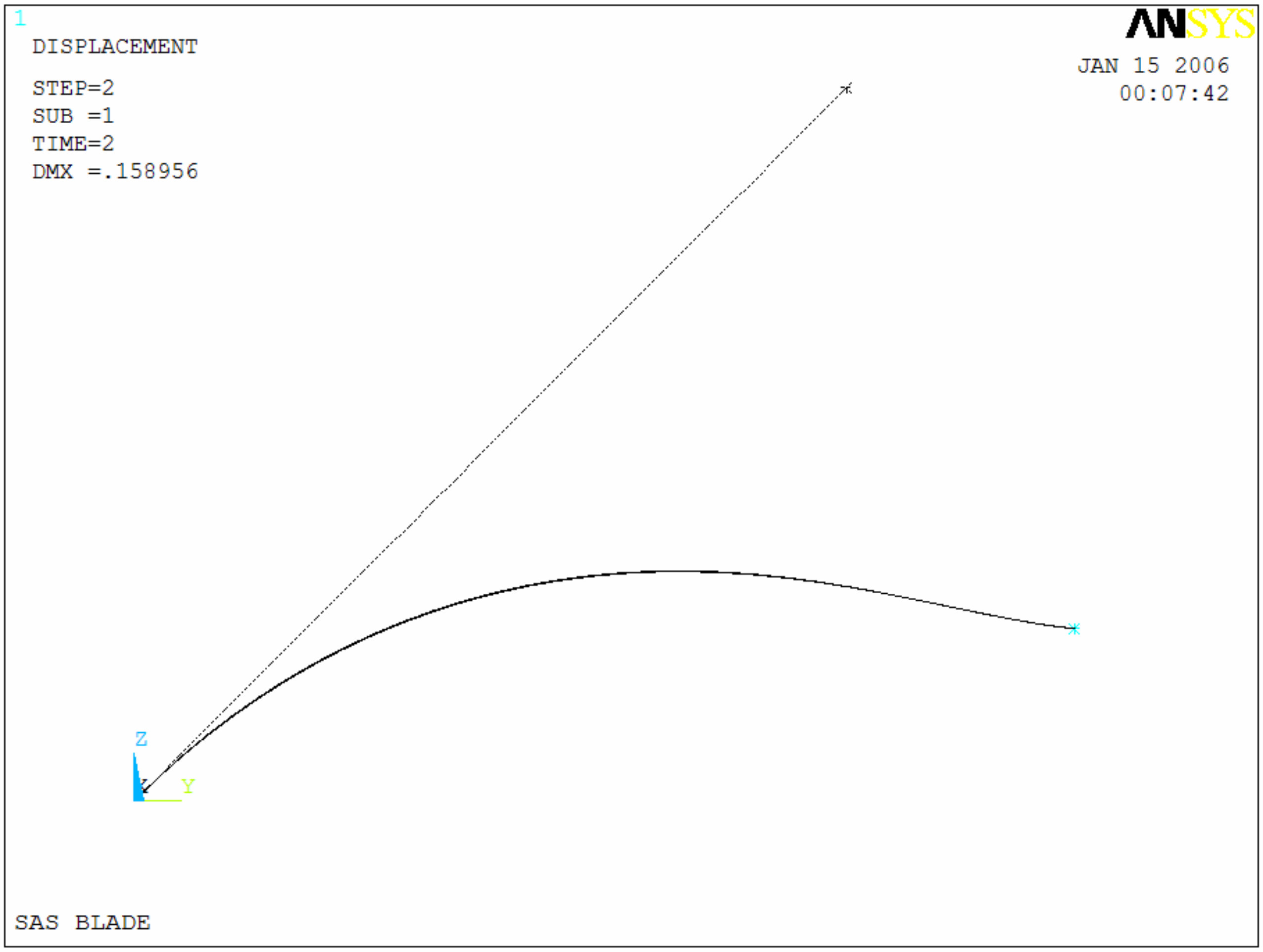
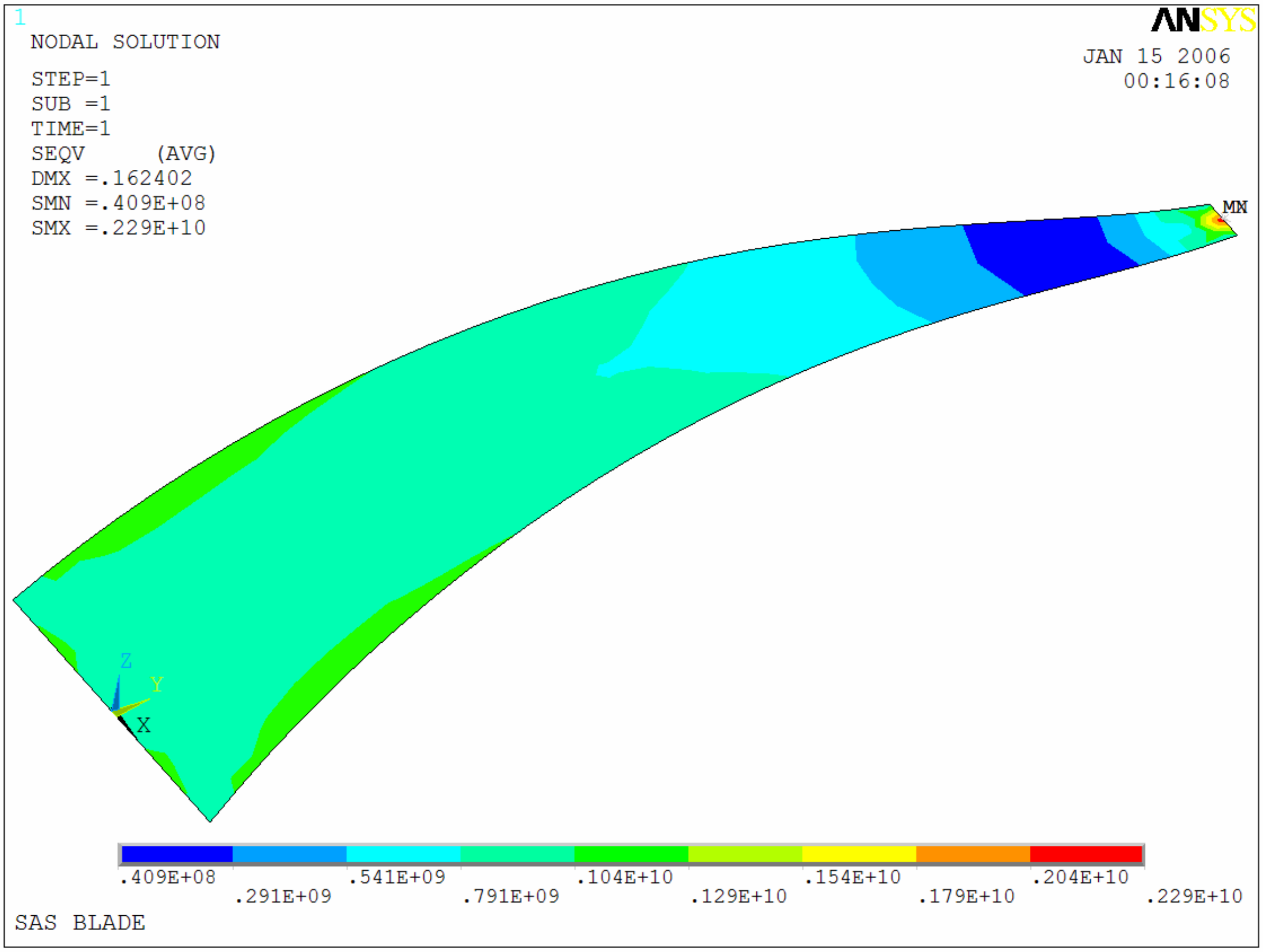
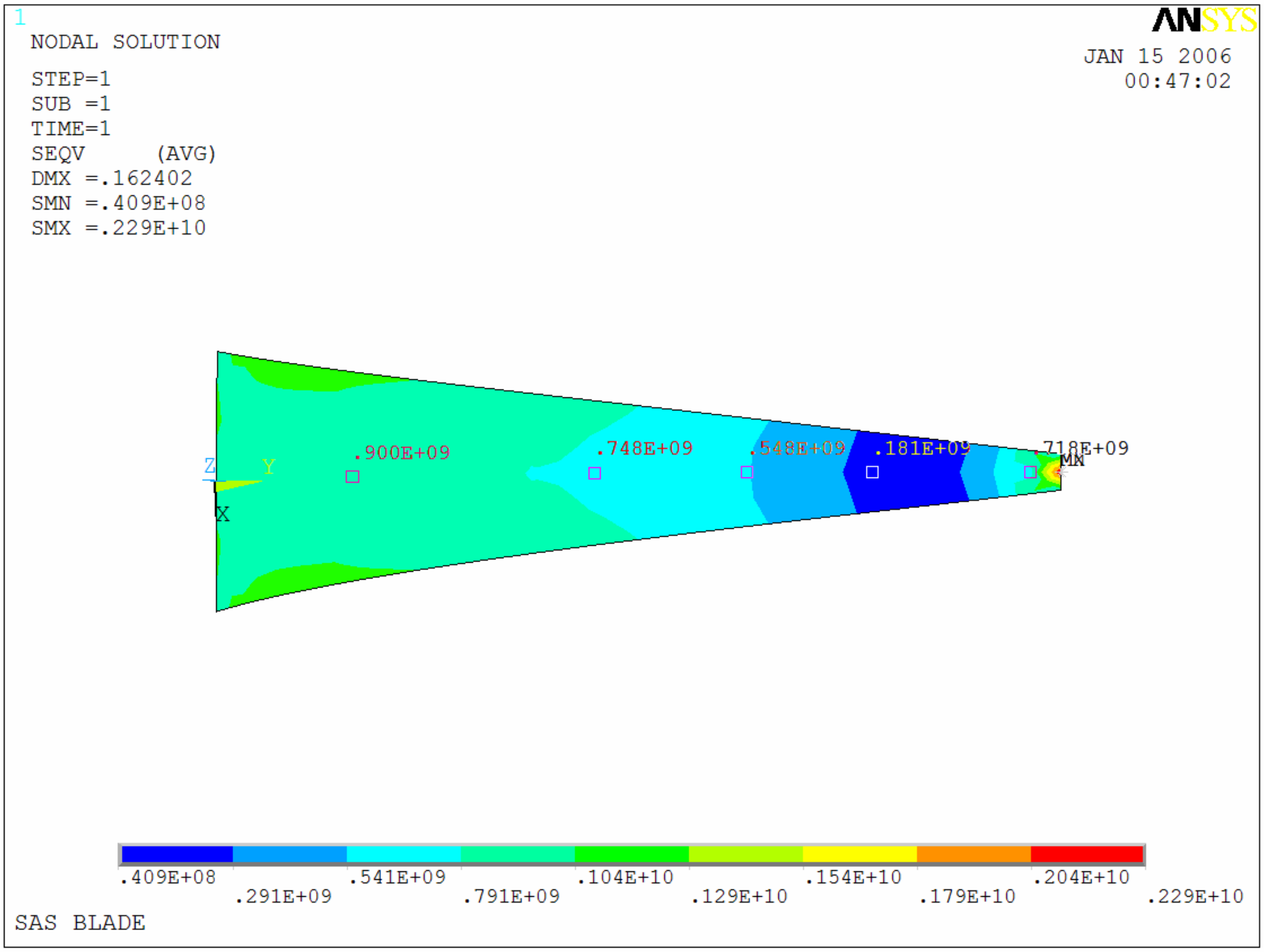

1
DISPLACEMENT
STEP=2
SUB =1
TIME=2
DMX =.158956
ANSYS
JAN 15 2006
00:07:42
Z
Y
SAS BLADE

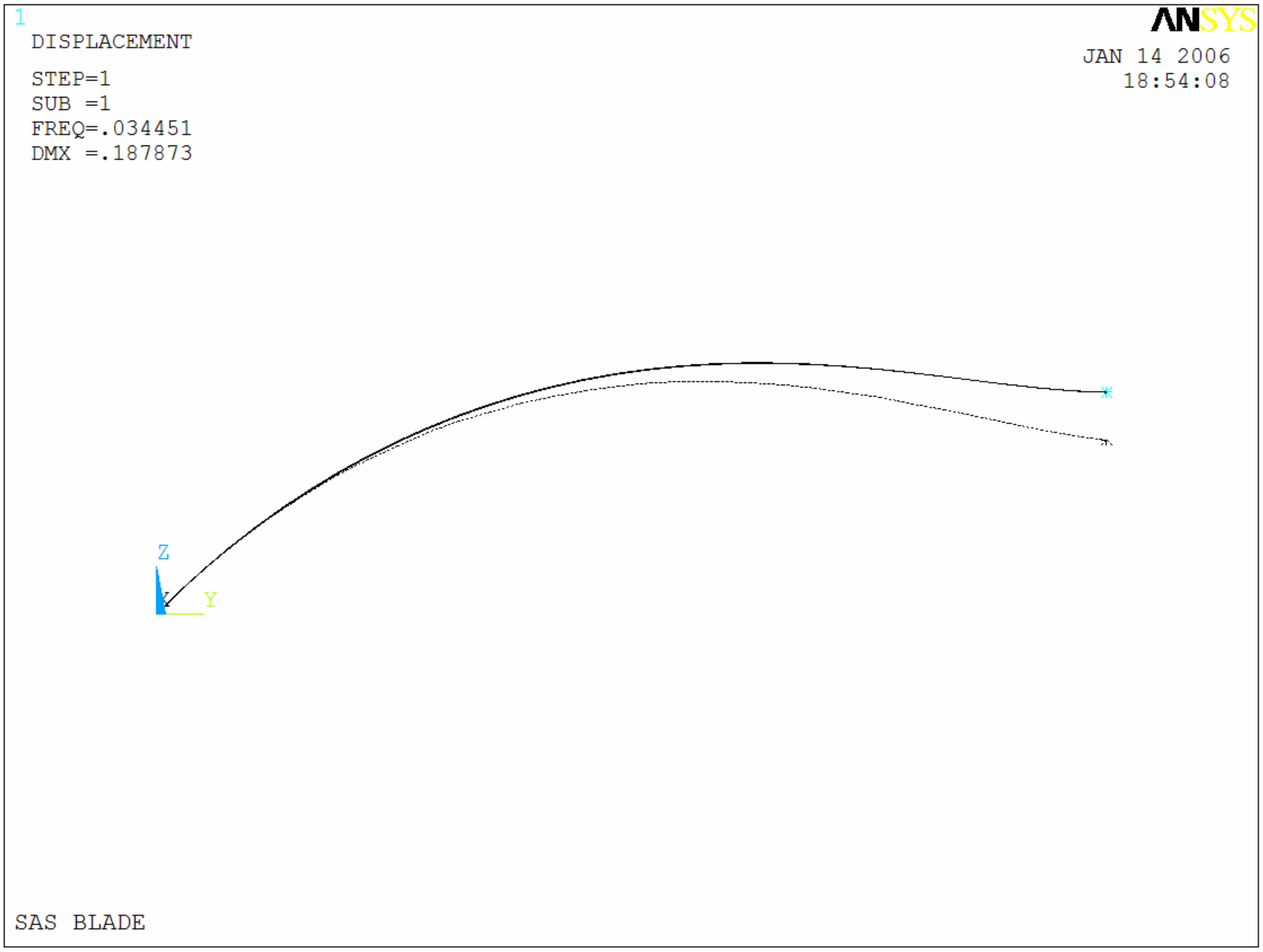
Figure 12: Stress Contours (von Mises) for the tuned position





The yield stress for maraging 250 is 1.9 GPa. With adequate constraints on the maximum deflection, the allowable stress can be ~2/3 of the yield stress, or 1.3 GPa. The maximum, non-localized, stress is ~1.3 GPa. The peak stress in the contour above is localized around the point load used in the model, i.e. is not realistic.

Figure 13: First Mode Shape near the low frequency tuned position



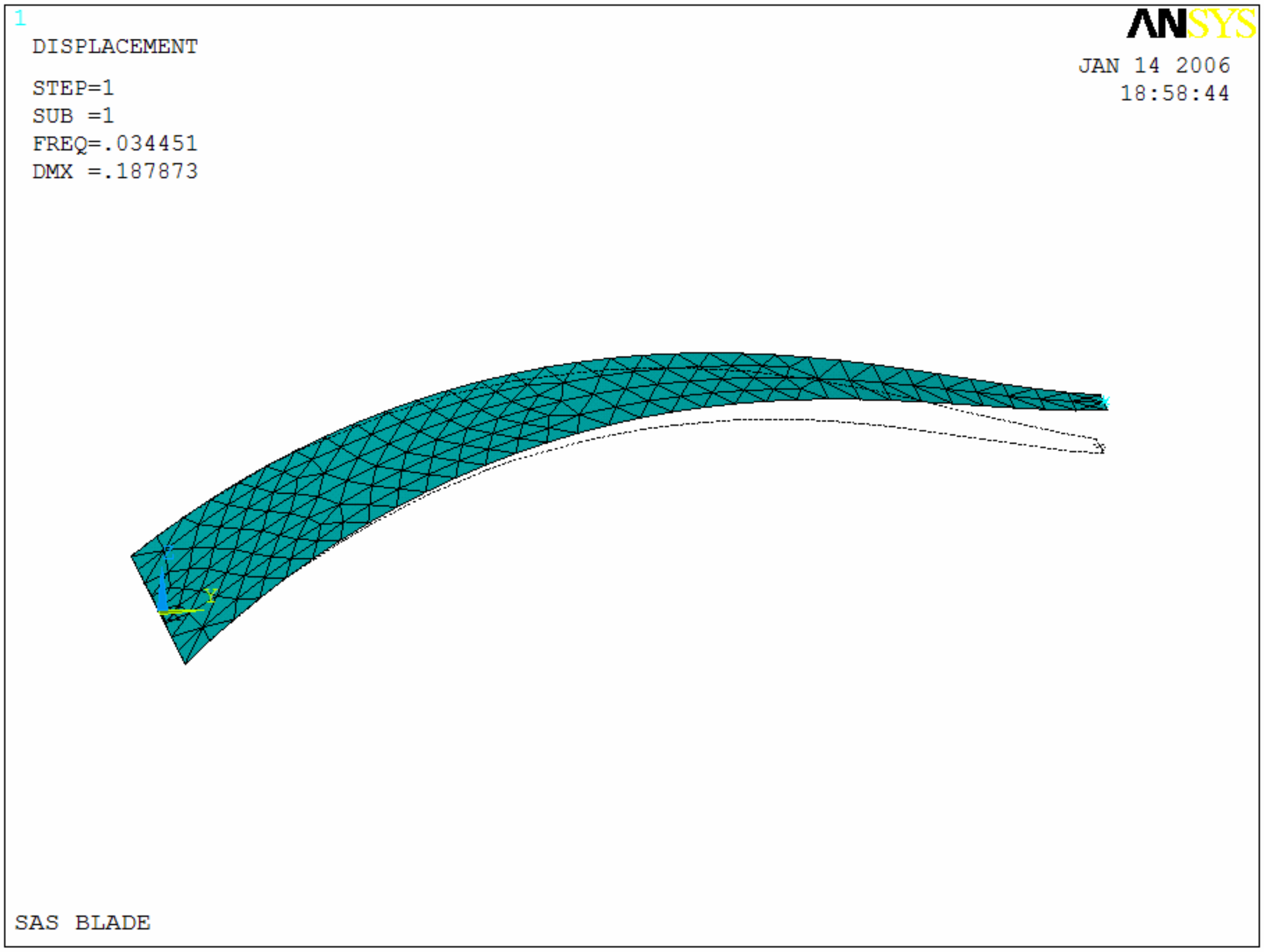
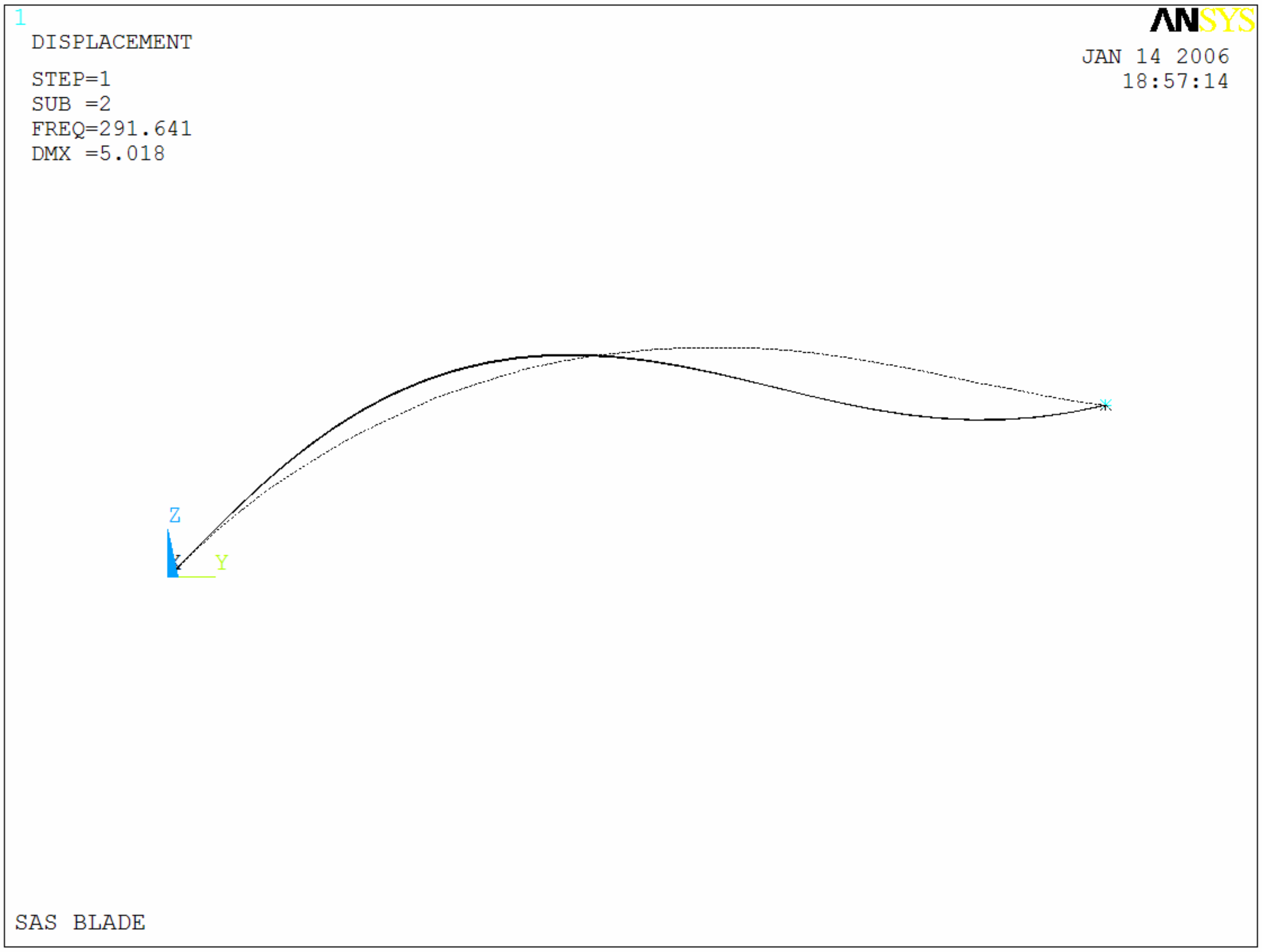

1
DISPLACEMENT
STEP=1
SUB =1
FREQ=.034451
DMX =.187873
ANSYS
JAN 14 2006
18:58:44
Y
X
SAS BLADE

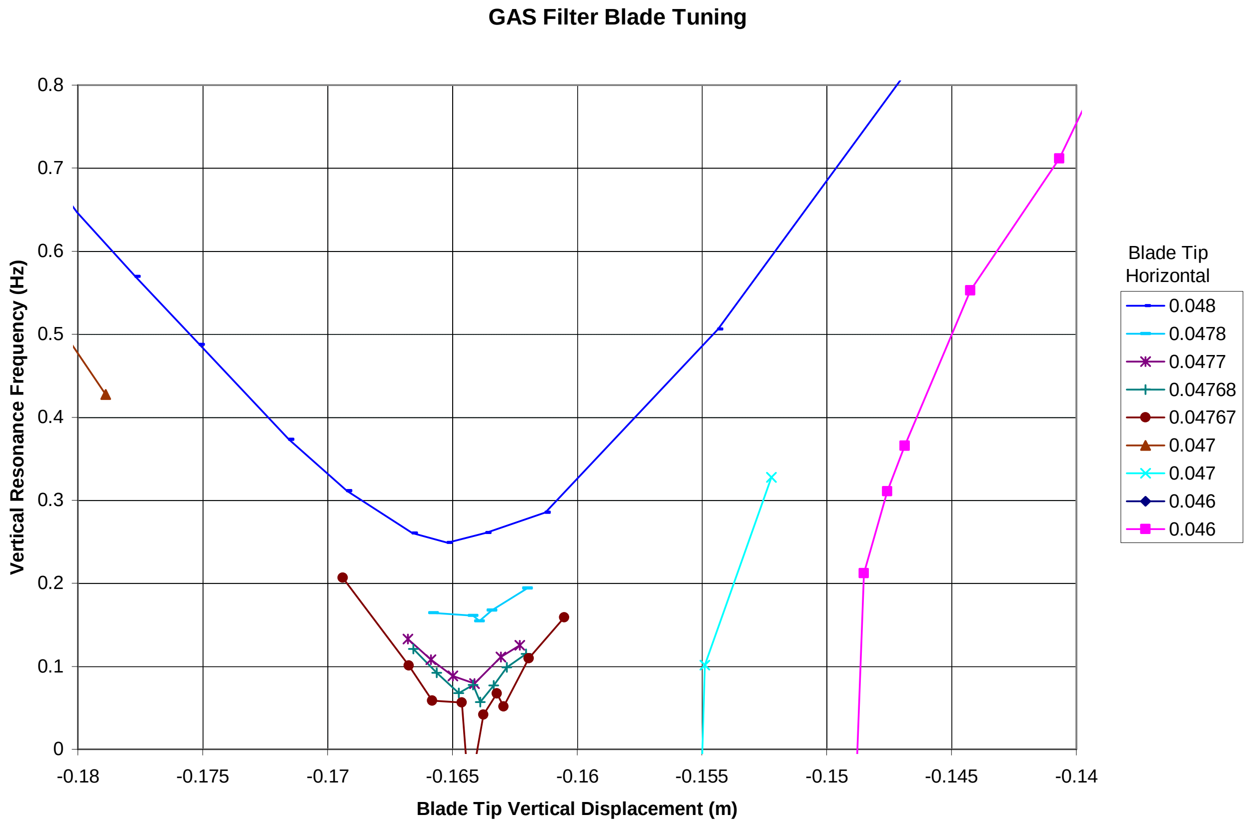
Figure 14: Second Mode Shape near the low frequency tuned position



3.4.1.2 Vertical Load Tuning

With the tip angle set to match the blade central support angle of 33 degrees, the blade spring can be tuned to a low frequency vertical resonance by adjusting the vertical load. Using this approach one maps out the tuning curves in Figure 15.

Figure 15: Vertical load tuning of the GAS Filter blade spring

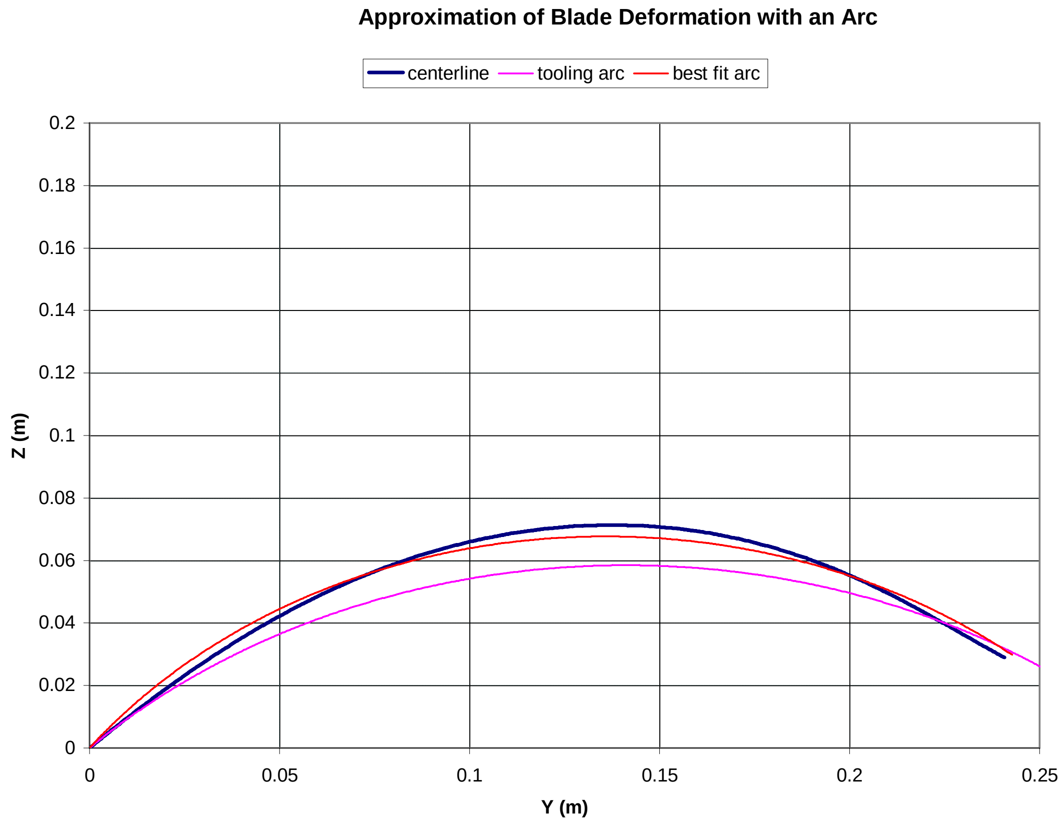


As indicated in the Figure, single GAS Filter blade tuning has been achieved in the analysis to ~50 mHz with precision of ~20 mHz. Numerical problems occur when attempting to tune to lower frequencies. The solution is extremely sensitive to horizontal displacement, e.g. 30 microns causes ~25 mHz shift. While this sensitivity could be a numerical artifact, the results further from the bifurcation point tend to support this extreme sensitivity behavior.

The position of the "sweet spot" for blade filter tuning is (at least to first order) independent of the blade thickness. However, one wants the static deflection to be close to the tuned position, i.e. one should not have to pull up with significant force to get close to the "sweet spot". For the above low frequency tuned position (dZ = -164 mm, dY = 47.7 mm), a vertical tuning force of approximately 80 N per blade is required, for each of the 32 blades, (compared to a total gravity load of 280 N per blade). Perhaps thicker blades or perhaps a different clamp angle is needed; Alternatively something is wrong with the analysis.

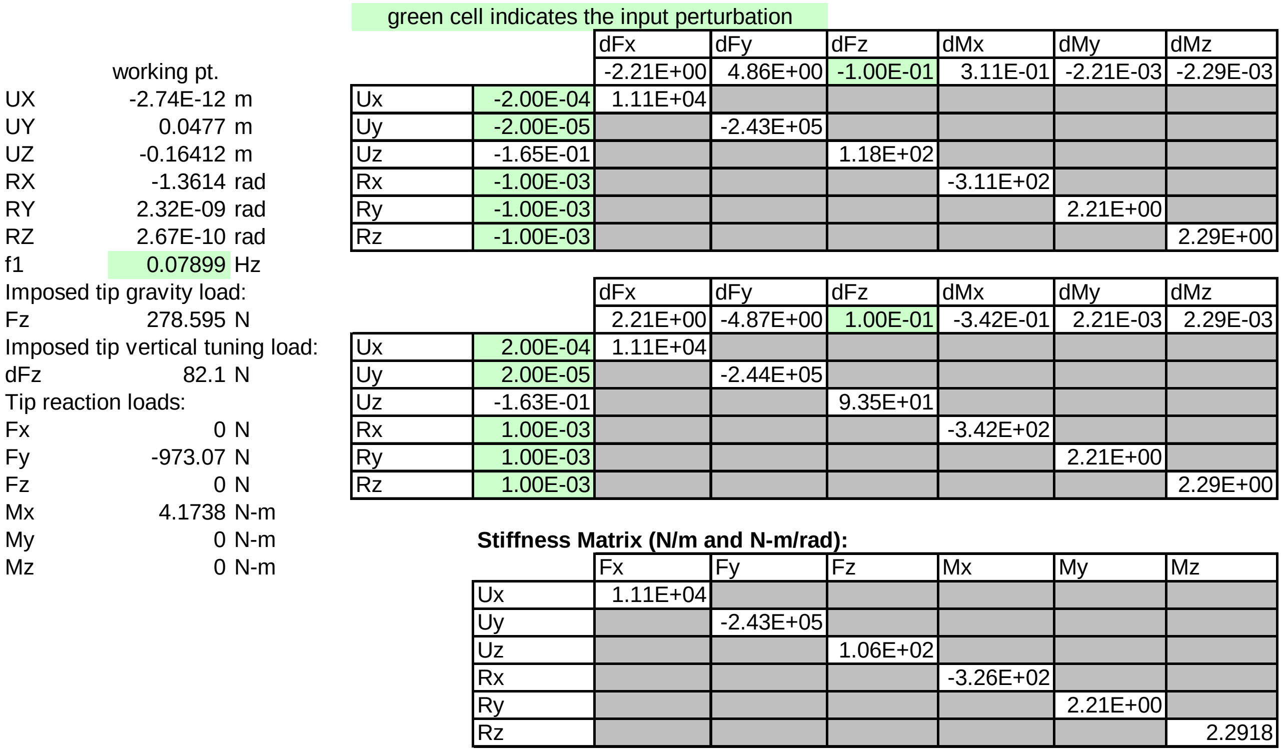
The calculated shape of the blade centerline is compared to the arc formed by the mounting blade tool (D050144). A circular arc is a reasonable approximation to the deformed blade shape at its low frequency tuned working point; This approximation may be used in a subsequent linear analysis of the coupled dynamics of the SAS system.

Figure 16: Deflected GAS Filter Blade Spring Centerline



The diagonal elements of the stiffness matrix at the nonlinear, pre-stressed working point have been calculated by imposing small plus and minus perturbations about the tuned working point. Given the possibility of numerical problems if tuned to the desired 30 mHz, a tuned frequency of 80 mHz was used instead (Figure 17). Note that the vertical stiffness does not include the negative (anti-) spring component; This is incorporated into the overall HAM-SAS system model by adjusting the vertical spring stiffness until the desired frequency is obtained.

Figure 17: Stiffness Matrix at the Working Point



green cell indicates the input perturbation

	working pt.	
UX	-2.74E-12	m
UY	0.0477	m
UZ	-0.16412	m
RX	-1.3614	rad
RY	2.32E-09	rad
RZ	2.67E-10	rad
f1	0.07899	Hz
Imposed tip gravity load:		
Fz	278.595	N
Imposed tip vertical tuning load:		
dFz	82.1	N
Tip reaction loads:		
Fx	0	N
Fy	-973.07	N
Fz	0	N
Mx	4.1738	N-m
My	0	N-m
Mz	0	N-m

		dFx	dFy	dFz	dMx	dMy	dMz
		-2.21E+00	4.86E+00	-1.00E-01	3.11E-01	-2.21E-03	-2.29E-03
Ux	-2.00E-04	1.11E+04					
Uy	-2.00E-05		-2.43E+05				
Uz	-1.65E-01			1.18E+02			
Rx	-1.00E-03				-3.11E+02		
Ry	-1.00E-03					2.21E+00	
Rz	-1.00E-03						2.29E+00

		dFx	dFy	dFz	dMx	dMy	dMz
		2.21E+00	-4.87E+00	1.00E-01	-3.42E-01	2.21E-03	2.29E-03
Ux	2.00E-04	1.11E+04					
Uy	2.00E-05		-2.44E+05				
Uz	-1.63E-01			9.35E+01			
Rx	1.00E-03				-3.42E+02		
Ry	1.00E-03					2.21E+00	
Rz	1.00E-03						2.29E+00

Stiffness Matrix (N/m and N-m/rad):

	Fx	Fy	Fz	Mx	My	Mz
Ux	1.11E+04					
Uy		-2.43E+05				
Uz			1.06E+02			
Rx				-3.26E+02		
Ry					2.21E+00	
Rz						2.2918

4 Dynamic Model

The overall HAM-SAS model (so far) includes the following aspects of the system:

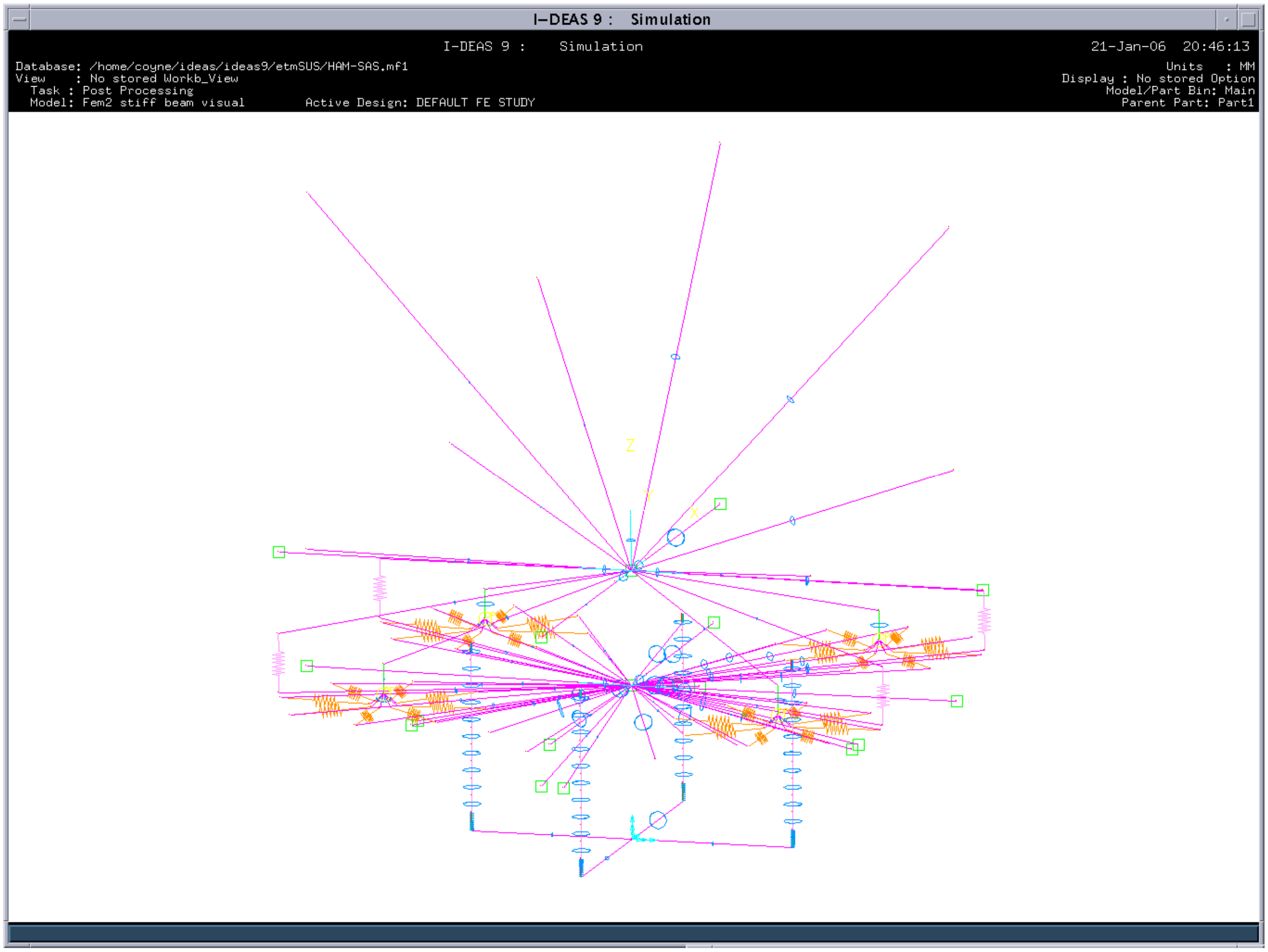
- IP flexures (top and bottom) modeled with beam elements
- IP tube modeled with beam elements
- The Spring-Box structure is modeled as a lumped mass (with moment of inertia matrix).
- The Optics Table structure is modeled as a lumped mass (with moment of inertia matrix).
- Each GAS Filter spring (32 total) is modeled as identical 6 degree-of-freedom springs, with the vertical spring stiffness tuned for ~50 mHz vertical frequency.
- The position of all actuators and sensors are represented by nodes with rigid links to their associated lumped center-of-mass (either the Spring Box or the Optics Table).
- The position of a number of cardinal payload points are represented by nodes with rigid links to the optics table lumped mass (center of mass), most notable the suspension point of a triple suspension at it's maximum offset from the table center.
- The quasi-kinematic mounting arrangement between the Optics Table and the GAS filter centers (4 contact points) are constrained to follow the translations of the GAS filter centers; The rotational degrees of freedom are not constrained. This seems appropriate for small motion (friction dominated) dynamics.

The following aspects are not modeled:

- The IP counterbalance mass (to set the center of percussion properly)
- The structure is only modeled to the base of the IP, i.e. the support structure (support table, support tubes and crossbeams) is not yet included.
- Structural compliance of the spring-box structure and the optics table.
- The internal modes of the blade springs

The model has been formulated with the I-DEAS finite element.

Figure 18: HAM-SAS System Model (isometric view)



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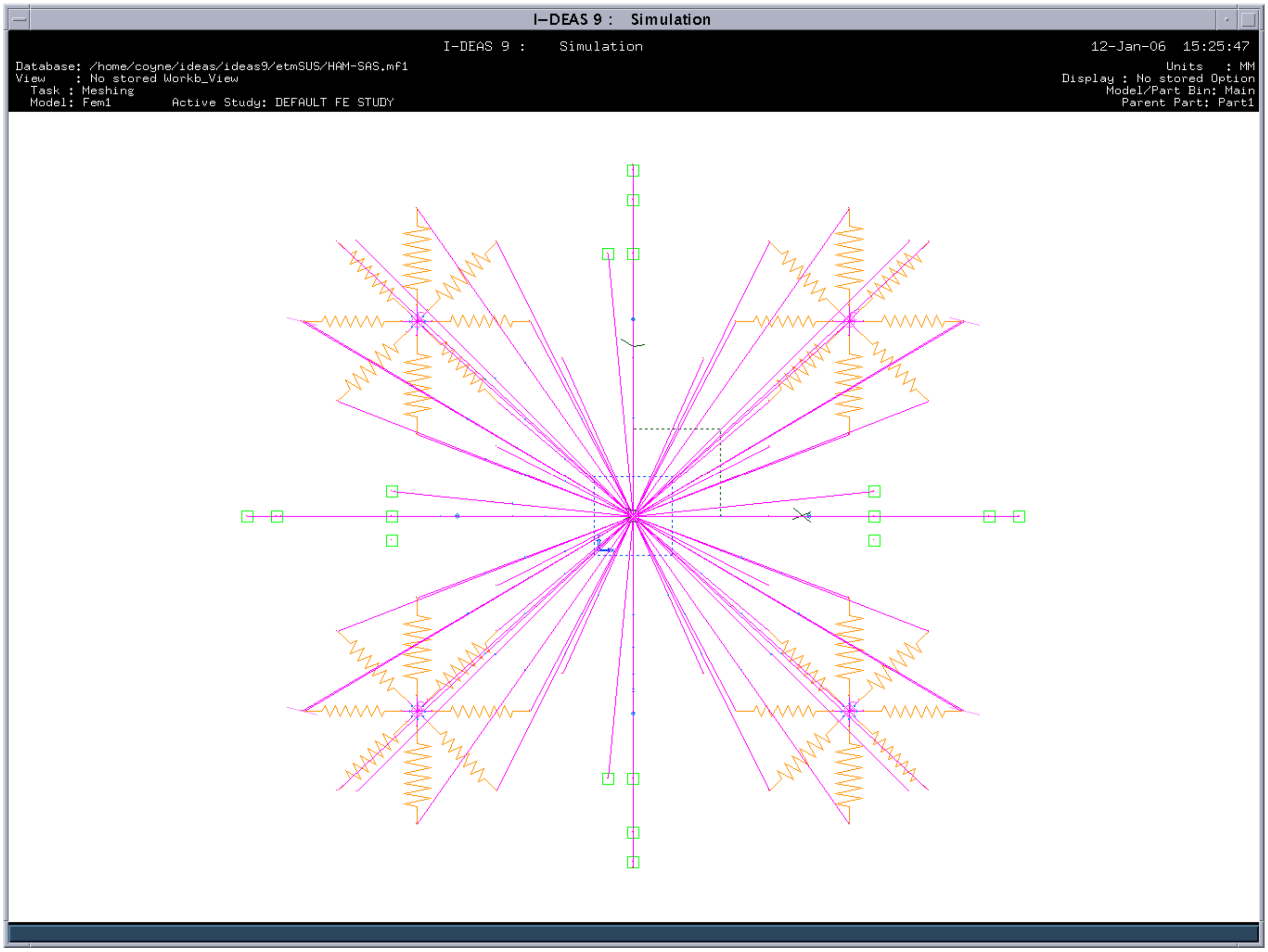
View     : No stored Workb_View                                                         Display : No stored Option
  Task : Post Processing                                                                     Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Design: DEFAULT FE STUDY                        Parent Part: Part1
```

Figure 19: HAM-SAS System Model (top view)



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                         I-DEAS 9 :     Simulation                             12-Jan-06  15:25:47
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View    : No stored Workb_View                                           Display : No stored Option
  Task : Meshing                                                               Model/Part Bin: Main
  Model: Fem1        Active Study: DEFAULT FE STUDY                            Parent Part: Part1
```
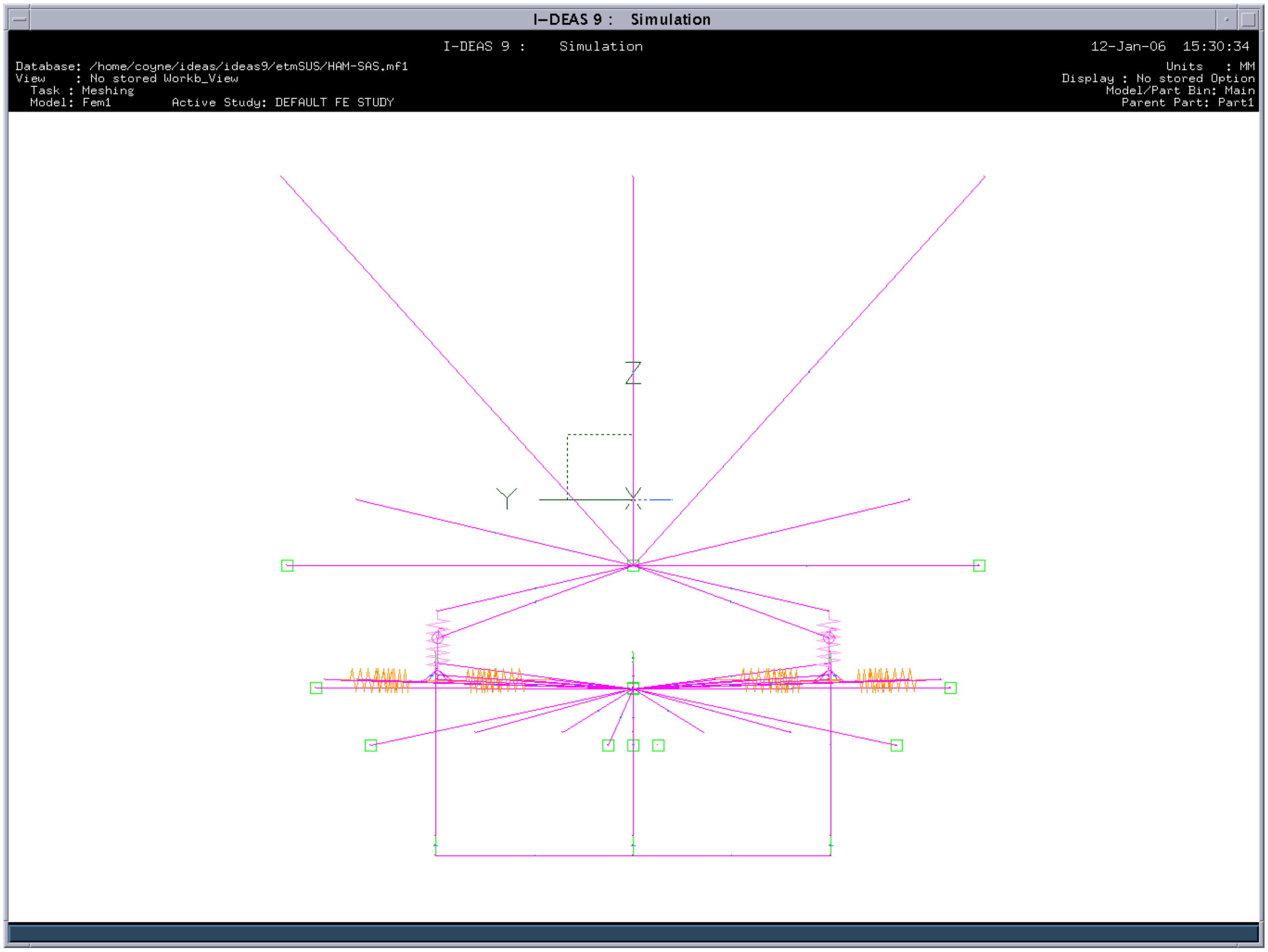

Figure 20: HAM-SAS System Model (side view)



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                         I-DEAS 9 :     Simulation                          12-Jan-06  15:30:34
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View    : No stored Workb_View                                           Display : No stored Option
  Task : Meshing                                                              Model/Part Bin: Main
  Model: Fem1         Active Study: DEFAULT FE STUDY                          Parent Part: Part1
```

4.1 Modal Analysis

With the I-DEAS finite element software it seems that one can't quite tune the system to 30 mHz IP or GAS modes due to numerical eigensolver limits. The Yaw mode is the lowest IP mode for IP frequencies > ~100 mHz. This is consistent with a previous[1] detailed finite element model of the HAM-SAS IP. However, as one tunes to lower frequencies the lateral IP modes become lower than yaw (slightly). In addition, cross-coupled x-y translational modes appear. I suspect that this may be an eigensolver precision problem. As the GAS filter is tuned to lower frequencies, the GAS filter and IP modes become coupled to some extent. To avoid numerical difficulties, the IP and the GAS filter modes were tuned to ~50 mHz (Table 1).

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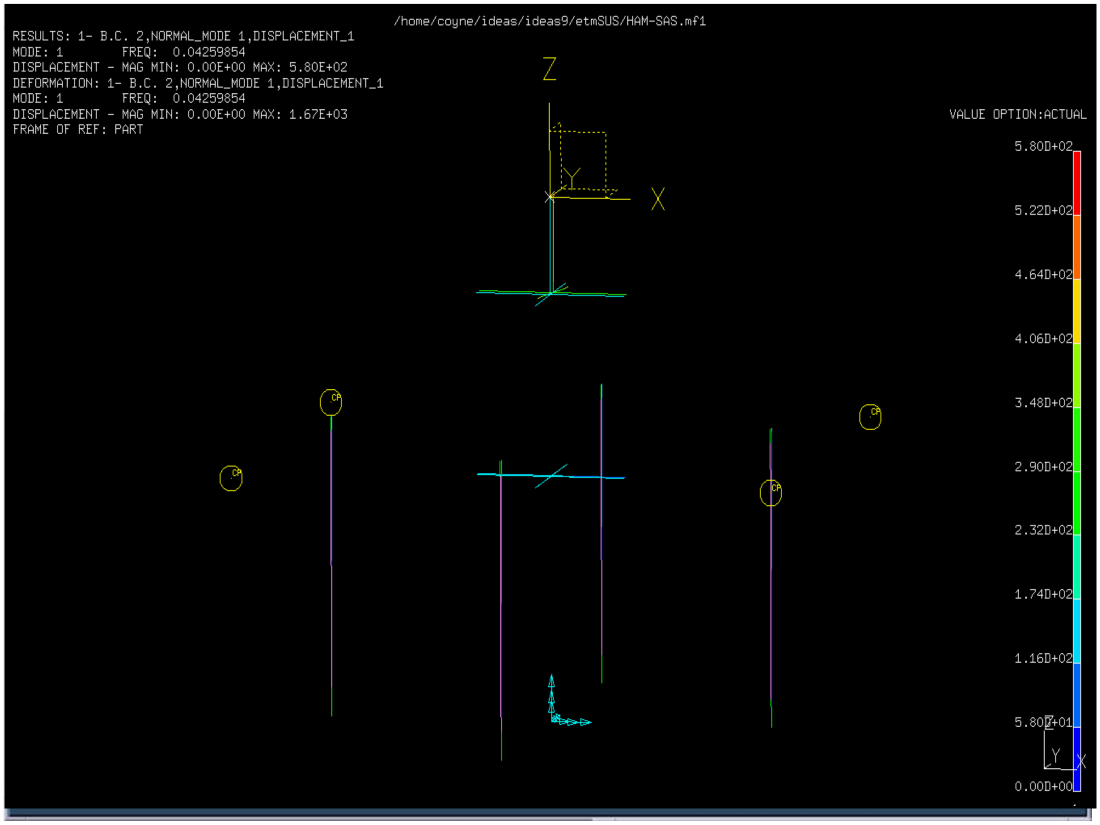
[1] Ilaria Taurasi, "Inverted Pendulum Studies for Seismic Attenuation", SURF project presentation, G050485-00, 9/20/2005.

Table 1: HAM-SAS System Modal Frequencies

Mode #	Frequency (Hz)	Shape
1	0.0426	Optics Table Y and -Rx
2	0.0514	System X
3	0.0537	Optics Table Z
4	0.0673	System Yaw
5	0.0708	System Y and +Rx
6	0.0736	System X and Ry
7	1.131	Spring Box +Yaw; Optics Table –Yaw
8	1.202	Spring Box +X; Optics Table –X
9	1.210	Spring Box +Y; Optics Table –Y
10	34.47	Spring Box Ry
11	42.17	Spring Box Rx
12	61.13	Spring Box Z
13 thru 20	369	IP tube 1st bending modes

The first 10 modes are depicted below. Click on the movie icon to the right of each mode shape image to see a short animation of the mode.

Figure 21: Mode Shapes



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RESULTS: 1- B.C. 2,NORMAL_MODE 1,DISPLACEMENT_1
MODE: 1        FREQ:  0.04259854
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 5.80E+02
DEFORMATION: 1- B.C. 2,NORMAL_MODE 1,DISPLACEMENT_1
MODE: 1        FREQ:  0.04259854
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 1.67E+03
FRAME OF REF: PART
VALUE OPTION:ACTUAL
```
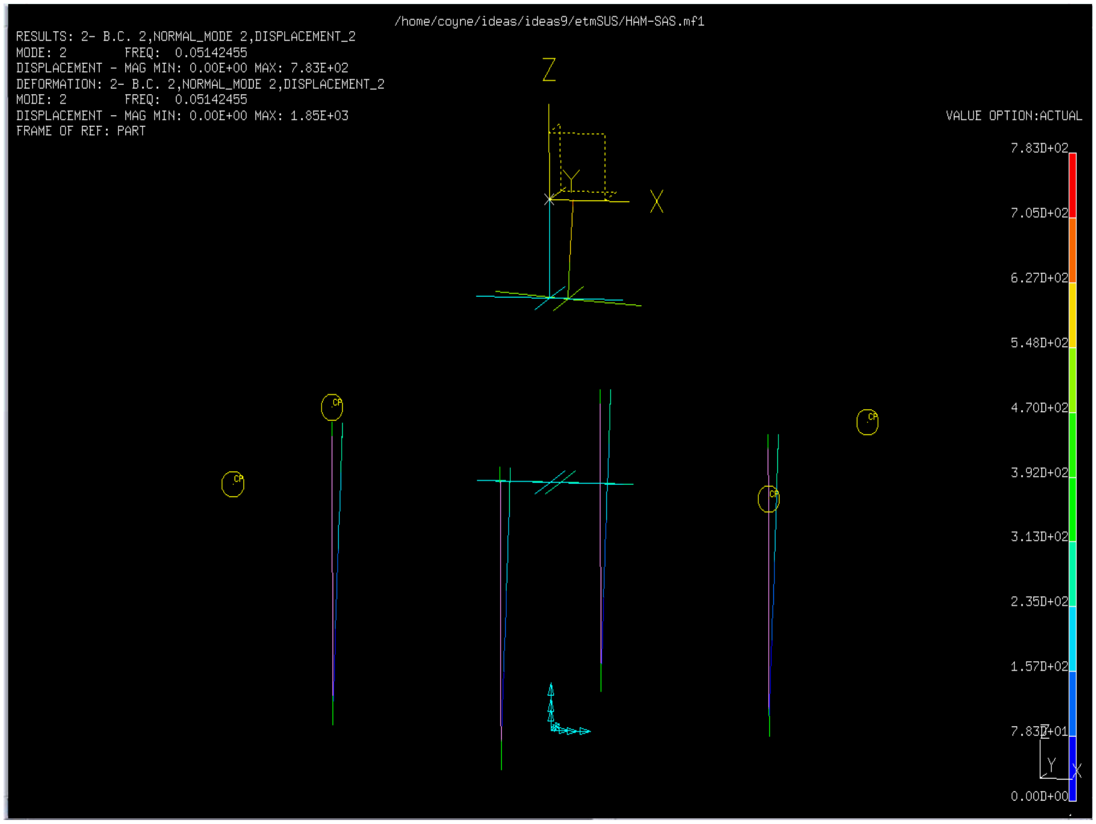
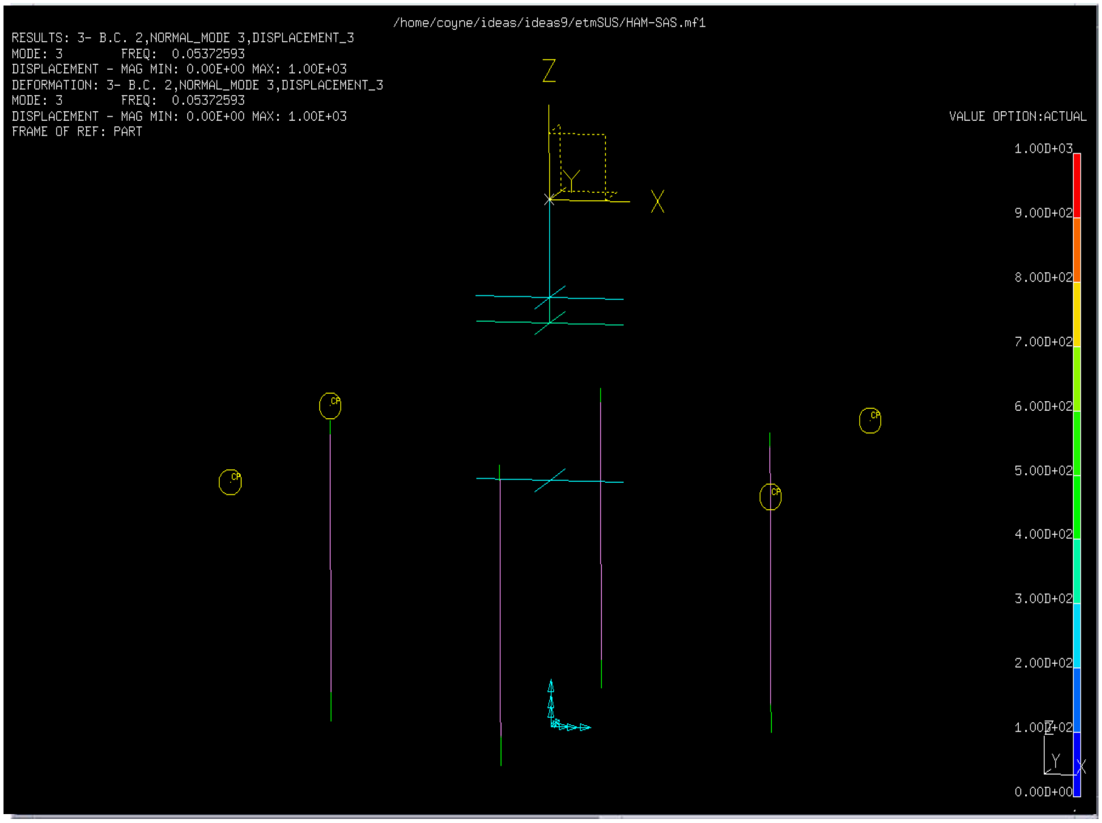

Mode 1



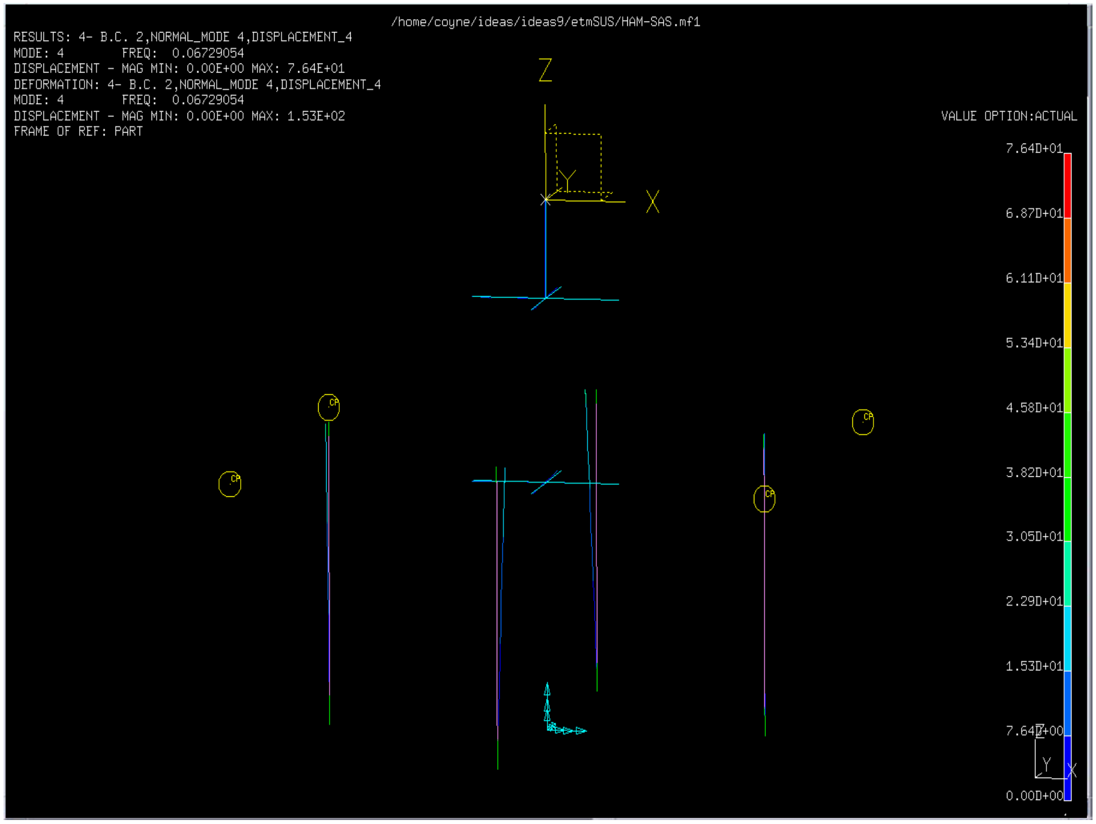
```
/home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1
RESULTS: 2- B.C. 2,NORMAL_MODE 2,DISPLACEMENT_2
MODE: 2        FREQ:  0.05142455
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 7.83E+02
DEFORMATION: 2- B.C. 2,NORMAL_MODE 2,DISPLACEMENT_2
MODE: 2        FREQ:  0.05142455
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 1.85E+03
FRAME OF REF: PART
VALUE OPTION:ACTUAL
```

mode 2



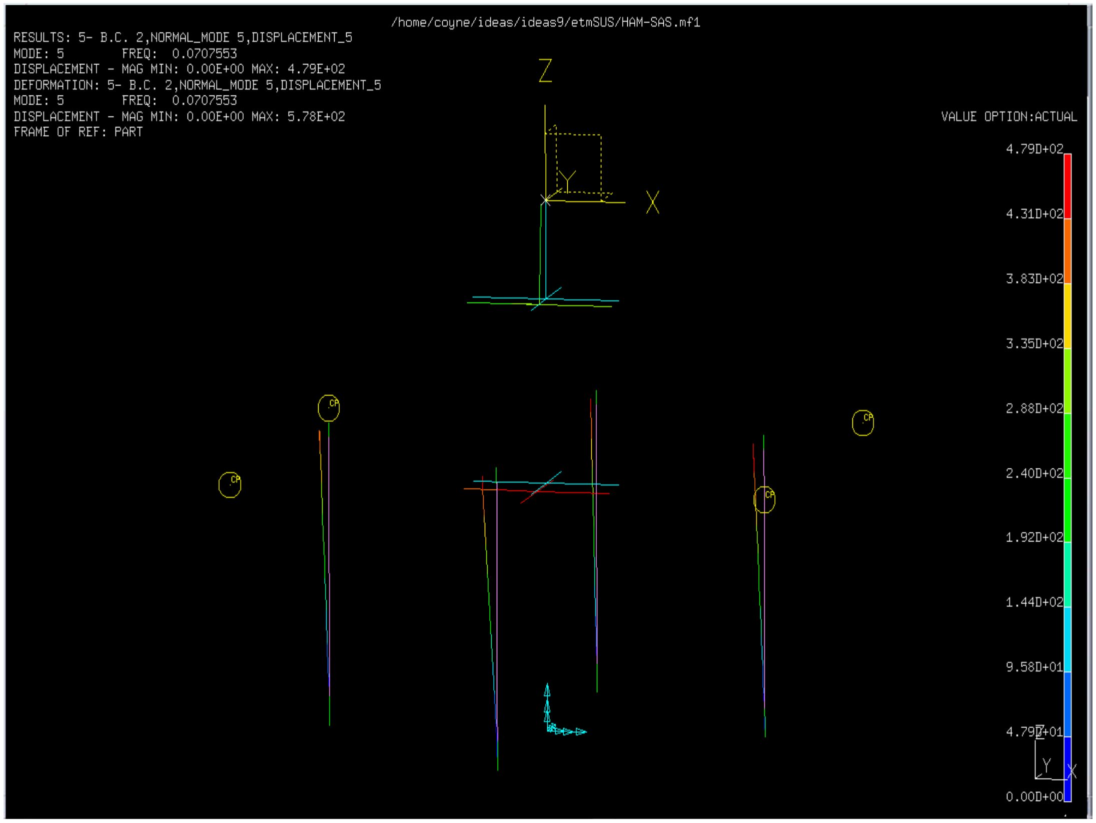
```
/home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1
RESULTS: 3- B.C. 2,NORMAL_MODE 3,DISPLACEMENT_3
MODE: 3        FREQ:  0.05372593
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 1.00E+03
DEFORMATION: 3- B.C. 2,NORMAL_MODE 3,DISPLACEMENT_3
MODE: 3        FREQ:  0.05372593
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 1.00E+03
FRAME OF REF: PART
```

Mode 3



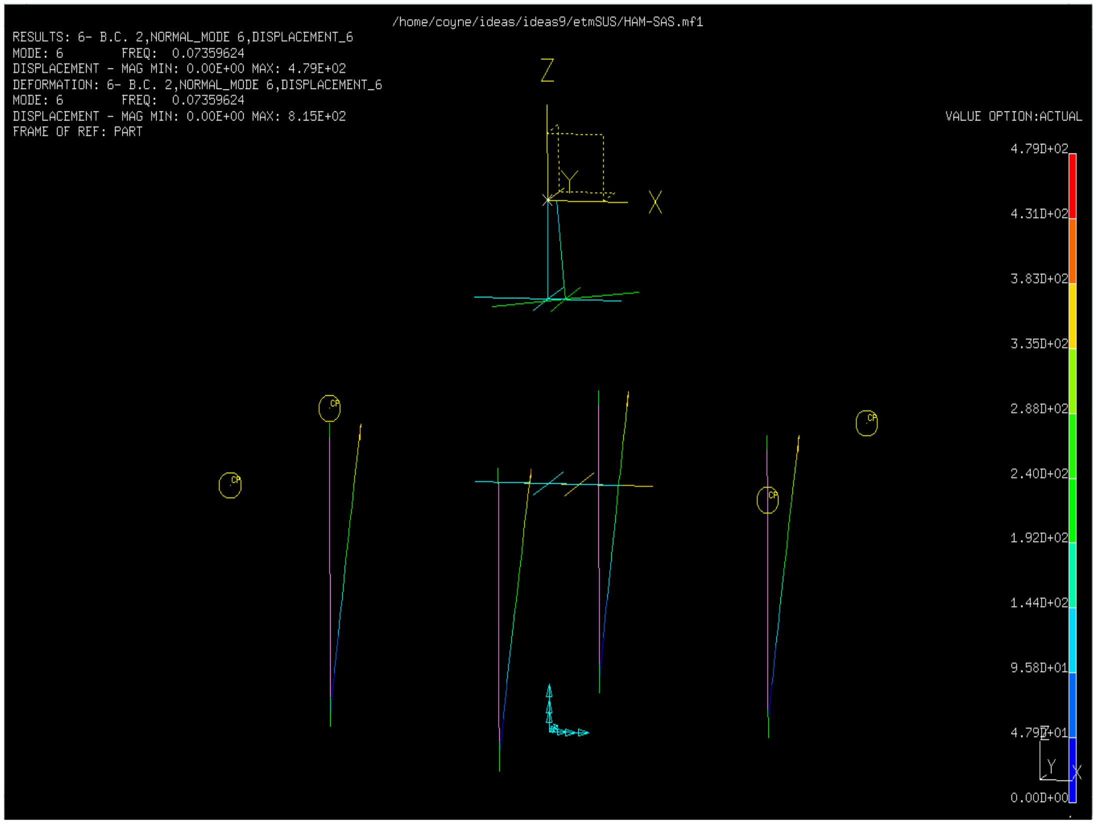
```
/home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1
RESULTS: 4- B.C. 2,NORMAL_MODE 4,DISPLACEMENT_4
MODE: 4        FREQ:  0.06729054
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 7.64E+01
DEFORMATION: 4- B.C. 2,NORMAL_MODE 4,DISPLACEMENT_4
MODE: 4        FREQ:  0.06729054
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 1.53E+02
FRAME OF REF: PART
```

Mode 4



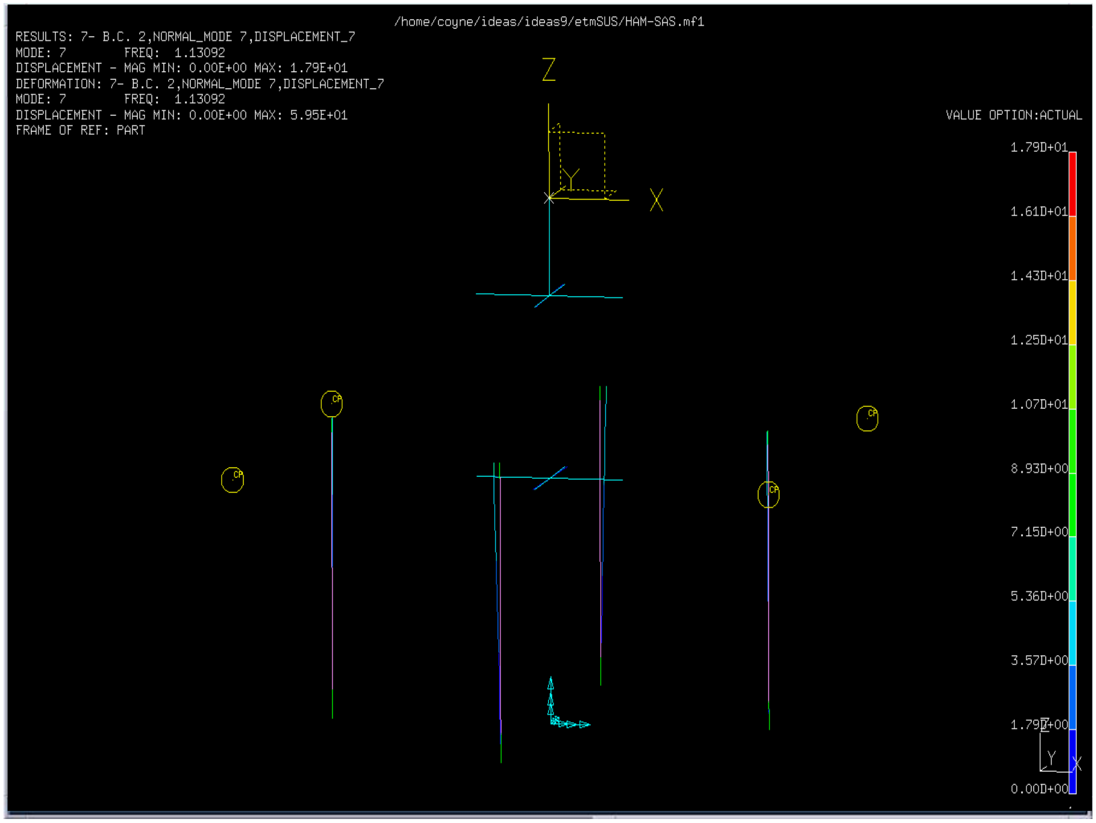
```
/home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1
RESULTS: 5- B.C. 2,NORMAL_MODE 5,DISPLACEMENT_5
MODE: 5        FREQ:  0.0707553
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 4.79E+02
DEFORMATION: 5- B.C. 2,NORMAL_MODE 5,DISPLACEMENT_5
MODE: 5        FREQ:  0.0707553
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 5.78E+02
FRAME OF REF: PART
```

Mode 5



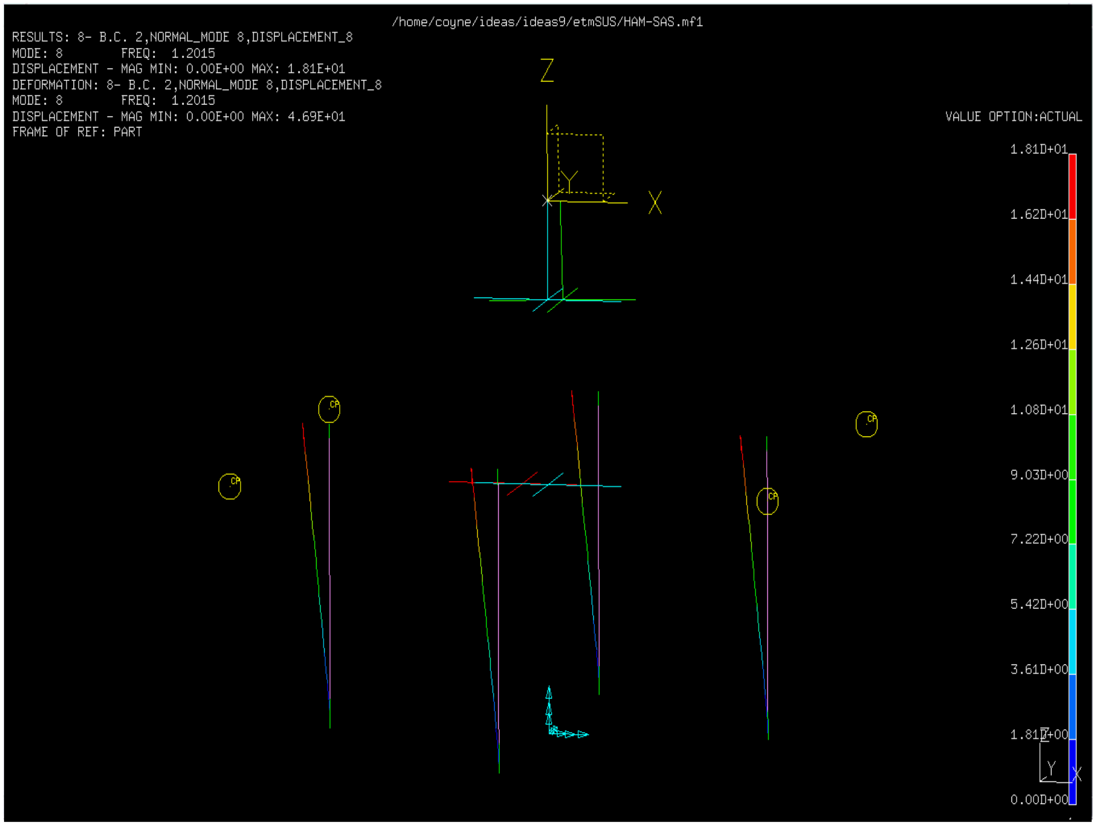
```
/home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1
RESULTS: 6- B.C. 2,NORMAL_MODE 6,DISPLACEMENT_6
MODE: 6        FREQ:  0.07359624
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 4.79E+02
DEFORMATION: 6- B.C. 2,NORMAL_MODE 6,DISPLACEMENT_6
MODE: 6        FREQ:  0.07359624
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 8.15E+02
FRAME OF REF: PART
```

Mode 6



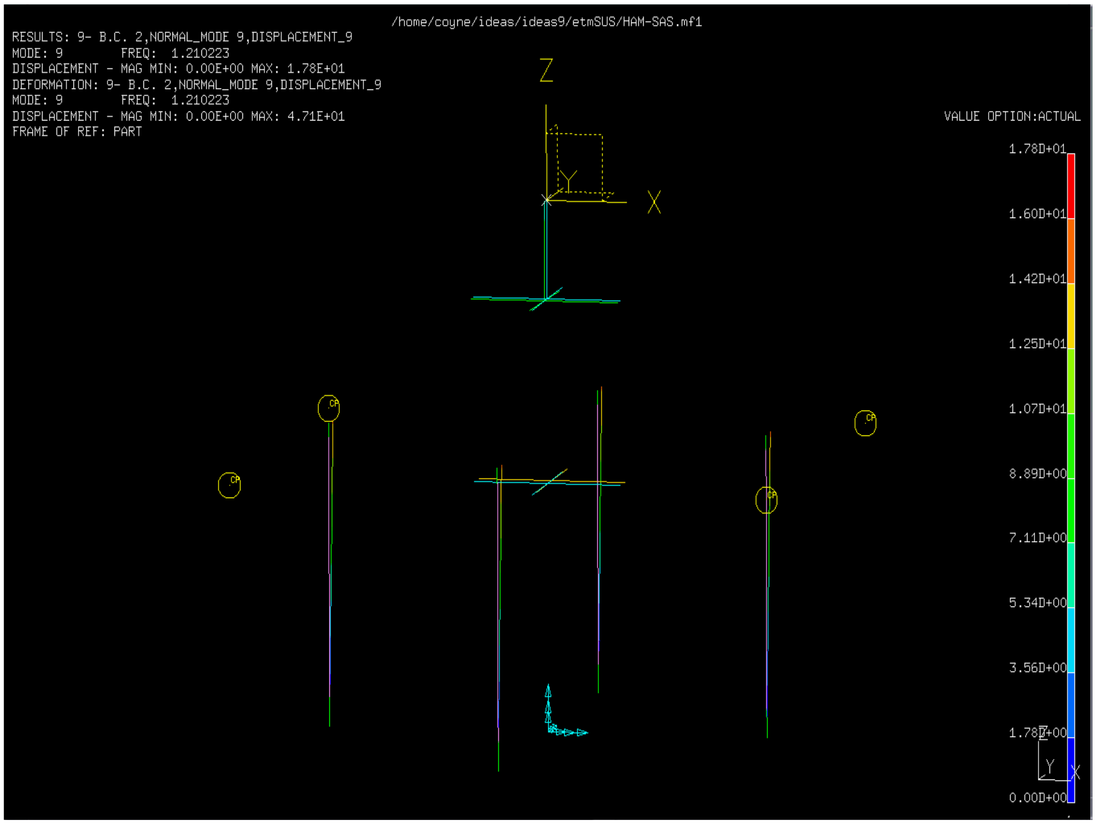
```
/home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1
RESULTS: 7- B.C. 2,NORMAL_MODE 7,DISPLACEMENT_7
MODE: 7        FREQ:  1.13092
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 1.79E+01
DEFORMATION: 7- B.C. 2,NORMAL_MODE 7,DISPLACEMENT_7
MODE: 7        FREQ:  1.13092
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 5.95E+01
FRAME OF REF: PART
```

Mode 7



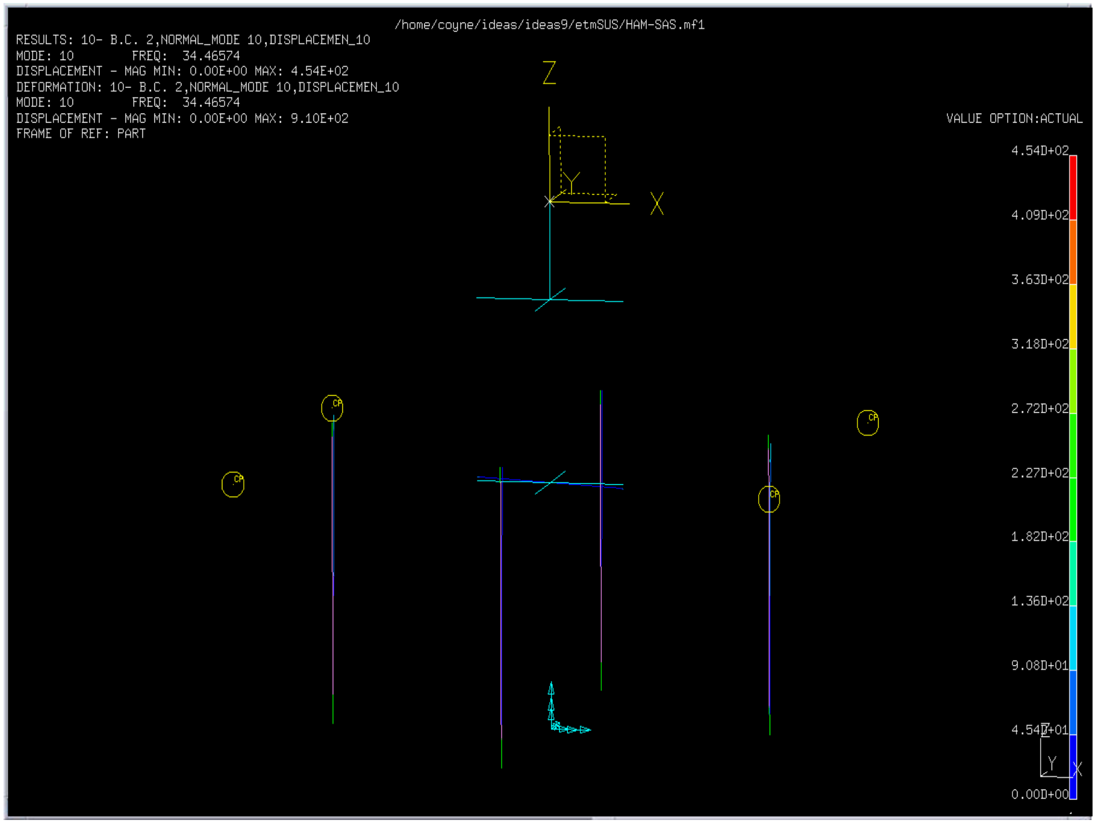
```
/home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1
RESULTS: 8- B.C. 2,NORMAL_MODE 8,DISPLACEMENT_8
MODE: 8        FREQ:  1.2015
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 1.81E+01
DEFORMATION: 8- B.C. 2,NORMAL_MODE 8,DISPLACEMENT_8
MODE: 8        FREQ:  1.2015
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 4.69E+01
FRAME OF REF: PART
```

Mode 8



```
/home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1
RESULTS: 9- B.C. 2,NORMAL_MODE 9,DISPLACEMENT_9
MODE: 9        FREQ:  1.210223
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 1.78E+01
DEFORMATION: 9- B.C. 2,NORMAL_MODE 9,DISPLACEMENT_9
MODE: 9        FREQ:  1.210223
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 4.71E+01
FRAME OF REF: PART
```

Mode 9



```
/home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1
RESULTS: 10- B.C. 2,NORMAL_MODE 10,DISPLACEMEN_10
MODE: 10        FREQ:  34.46574
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 4.54E+02
DEFORMATION: 10- B.C. 2,NORMAL_MODE 10,DISPLACEMEN_10
MODE: 10        FREQ:  34.46574
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 9.10E+02
FRAME OF REF: PART
```

Mode 10

4.2 Modal Damping

Riccardo DeSalvo and Yumei Huang have recently measured the HAM-SAS IP damping, using a platform with 3 IP legs, from 1 Hz down to 60 mHz. The damped frequency and the time to ring down to 1/e of the initial amplitude was used to measure the Q. The data are represented well by the following fit:

$$Q = \frac{f^2}{1.6\,10^5\left(f^2 + 19.6\right)}$$

where f is the frequency in Hz. The Q at 60 mHz is 11.5 and the Q is predicted to be 2.9 at 30 mHz. Using this Q(f) function, the equivalent viscous damping ratio (fraction of critical damping, $\varsigma = {}^{1}\!/_{2Q}$) was calculated and set for each mode, as indicated in Table 2. A maximum Q of 10,000 was assumed for frequencies above 2 Hz.

Table 2: Modal Frequencies and Damping Factors

Mode #	Frequency(Hz) Undamped	Modal Prop. Mass	% X-Mass	% Y-Mass	% Z-Mass	--Damping Factors-- % Viscous	% Hysteretic
*1	0.0426	4.20916e+08	0.00	33.52	0.00	8.64	0.00
*2	0.0514	7.16426e+08	53.55	0.00	0.00	5.94	0.00
*3	0.0537	9.12652e+08	0.00	0.00	63.00	5.44	0.00
*4	0.0673	1.5932e+07	0.10	1.03	0.00	3.46	0.00
*5	0.0708	2.63828e+08	0.01	65.40	0.00	3.13	0.00
*6	0.0736	3.35173e+08	46.30	0.01	0.00	2.90	0.00
*7	1.1309	580568	0.00	0.00	0.00	0.01	0.00
*8	1.2015	282983	0.00	0.00	0.00	0.01	0.00
*9	1.2102	278894	0.00	0.00	0.00	0.01	0.00
*10	34.4657	1.6941e+08	0.00	0.00	0.00	0.01	0.00
*11	42.1714	1.42094e+08	0.00	0.00	0.00	0.01	0.00
*12	61.1331	5.24846e+08	0.00	0.00	36.96	0.01	0.00
*13	369.4467	260.802	0.00	0.00	0.00	0.01	0.00
*14	369.4487	180.837	0.00	0.00	0.00	0.01	0.00
*15	369.4545	365.033	0.00	0.00	0.00	0.01	0.00
*=Active			99.98	99.98	99.96		

Rigid-Body Mode Frequency Tolerance (Hz) 0.001

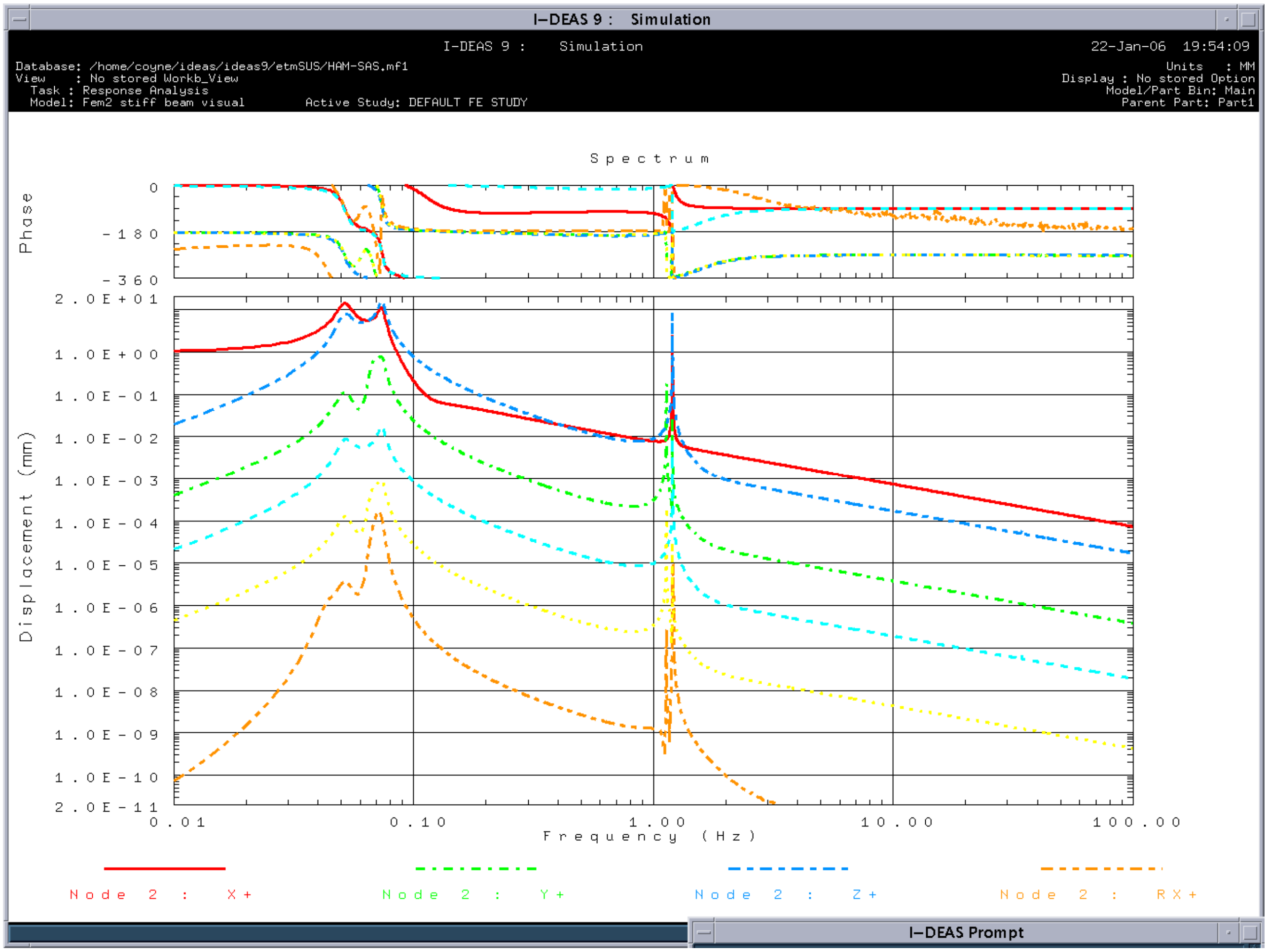
4.3 Transfer Functions

4.3.1 “Ground” to Triple Suspension Point

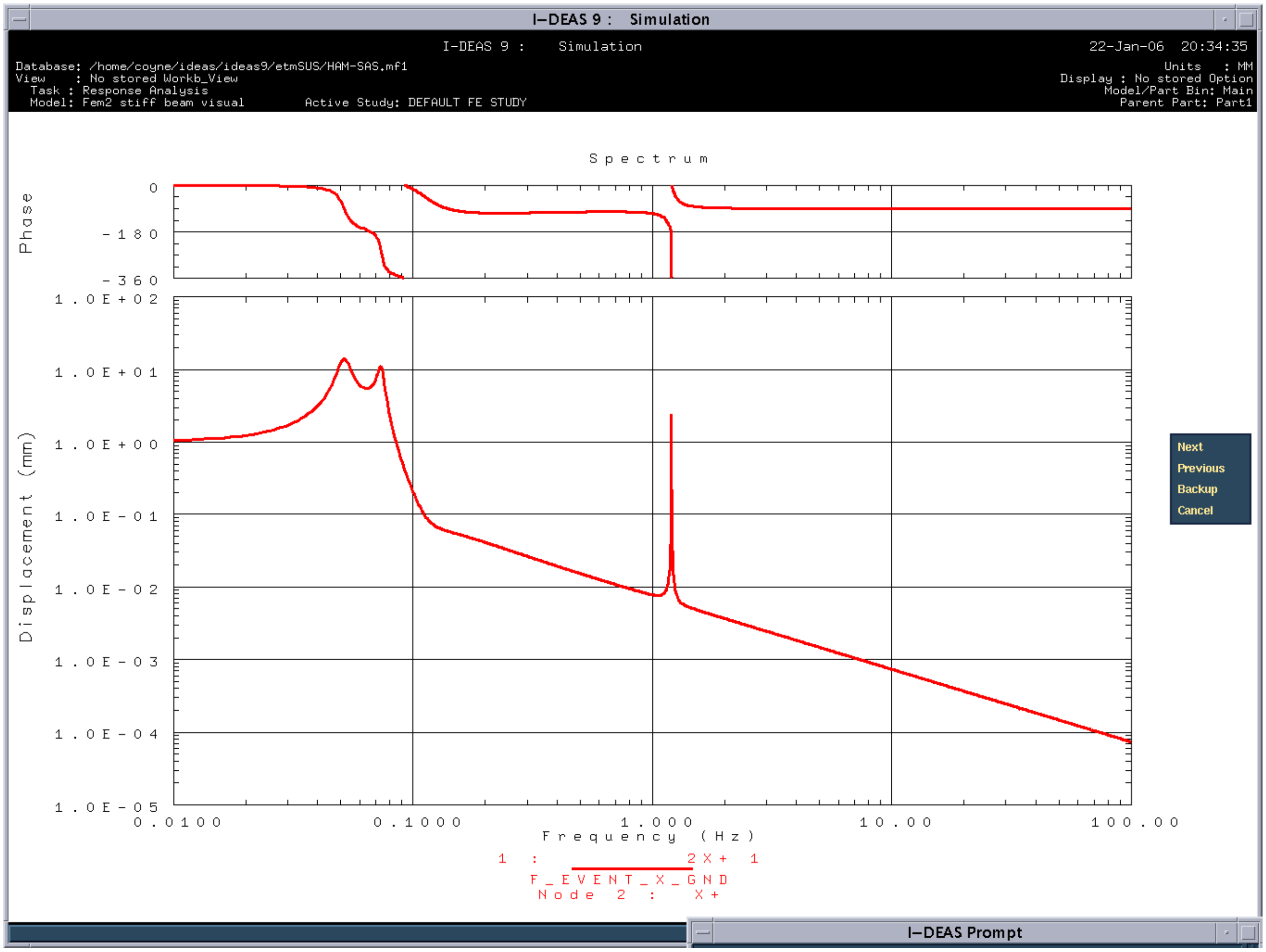
Since the support structure model has not yet been integrated with the HAM-SAS model, the “ground” motion excitation is imposed at the base of the 4 IPs. The resulting motion at the suspension point of an offset triple suspension system is shown in the following 36 transfer function plots (6 ground motion dofs x 6 suspension point dofs).

N.B.: The following plots are not actually transfer functions per se, they are the response to an excitation with a frequency independent, 1 mm amplitude spectrum for translations and 1 rad for rotations. Consequently a 1 mm translation response corresponds to a unity transfer function. Likewise a 1 rad rotation response corresponds to a unity transfer function. For a ground (base) excitation of 1 rad in rotation, the translational response at DC (i.e. without dynamic amplification) is simply the distance (moment arm) of the response point from the ground (base).

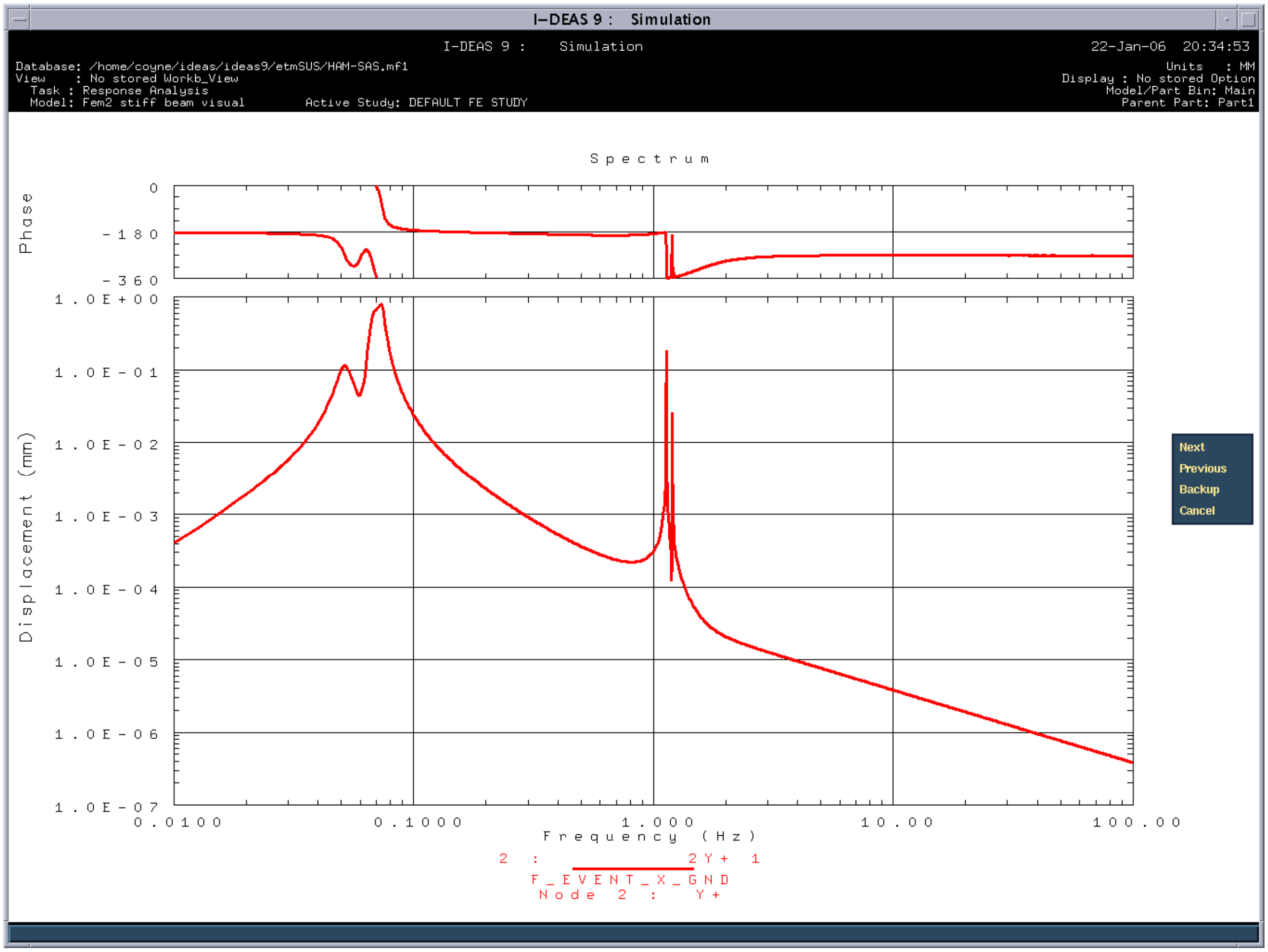
Figure 22: X Ground Motion to Suspension Point Motion



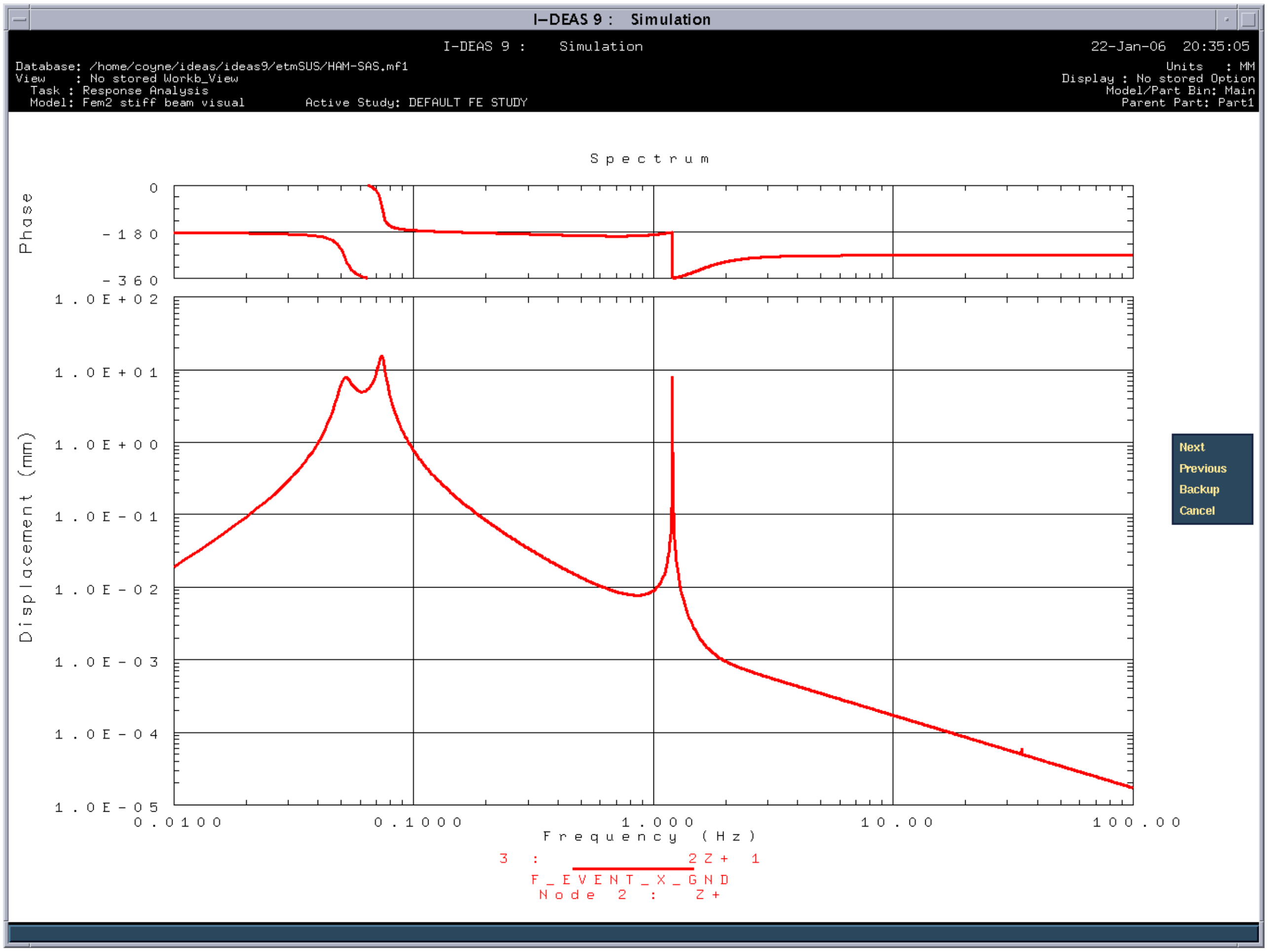
```
I-DEAS 9 :     Simulation                                    22-Jan-06  19:54:09
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                   Units   : MM
View    : No stored Workb_View                           Display : No stored Option
  Task : Response Analysis                                    Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY      Parent Part: Part1
```



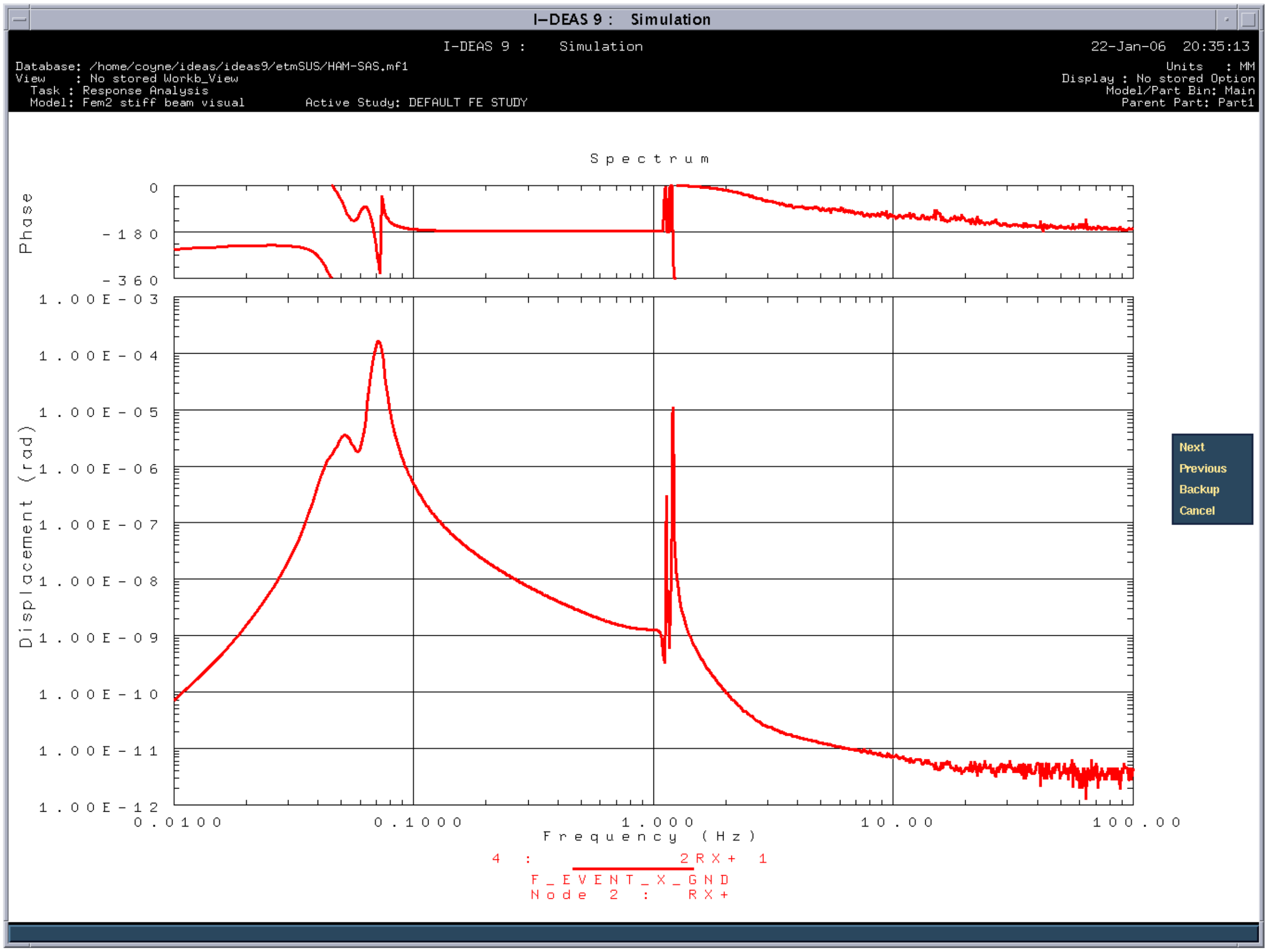
```
                         I-DEAS 9 :     Simulation                          22-Jan-06   20:34:35
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                                Units    : MM
View     : No stored Workb_View                                        Display : No stored Option
  Task : Response Analysis                                                 Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY         Parent Part: Part1
```



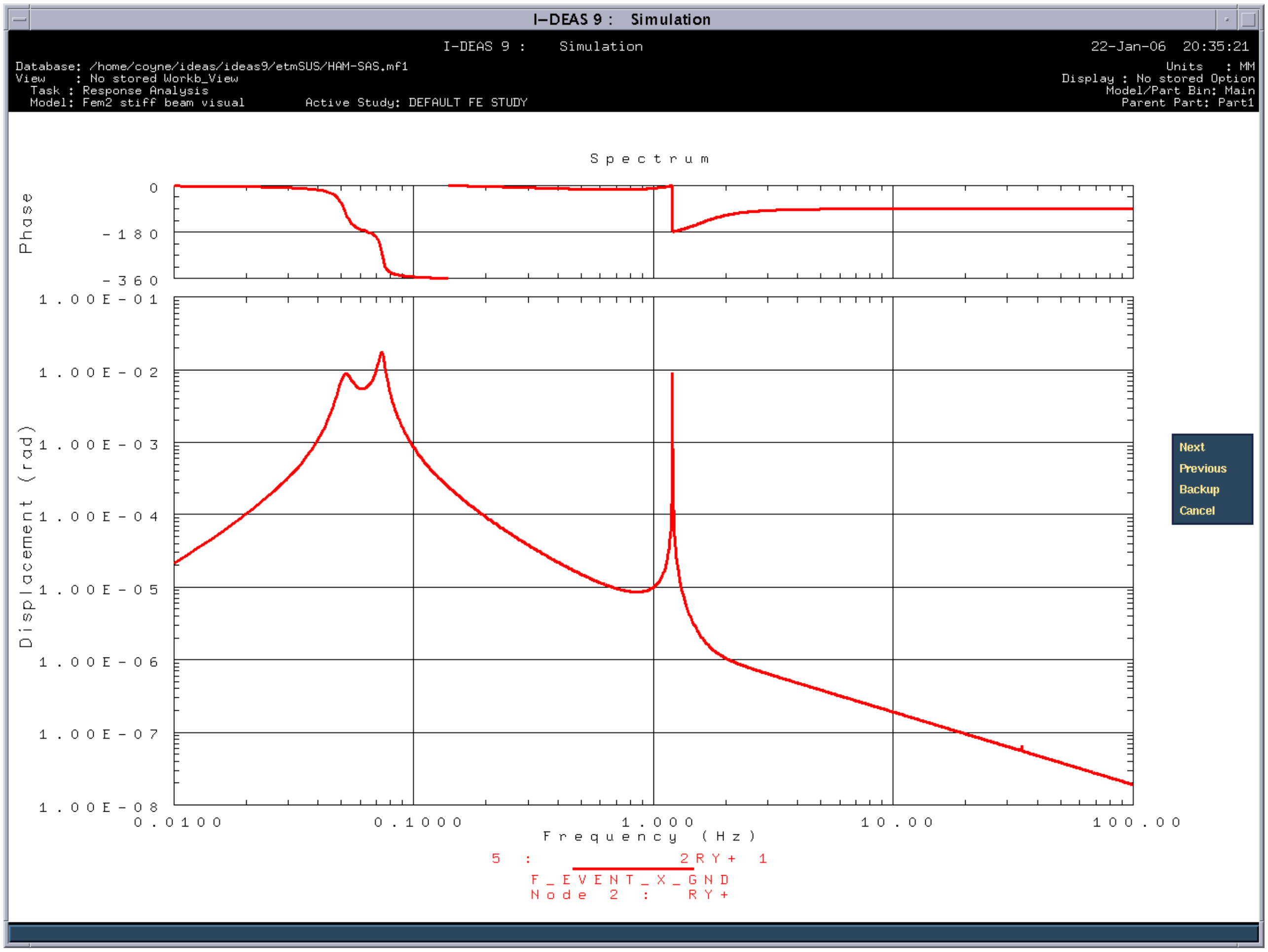
```
I-DEAS 9 :  Simulation

                              I-DEAS 9 :    Simulation                              22-Jan-06   20:34:53
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                                     Units    : MM
View    : No stored Workb_View                                             Display : No stored Option
  Task : Response Analysis                                                      Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY            Parent Part: Part1
```



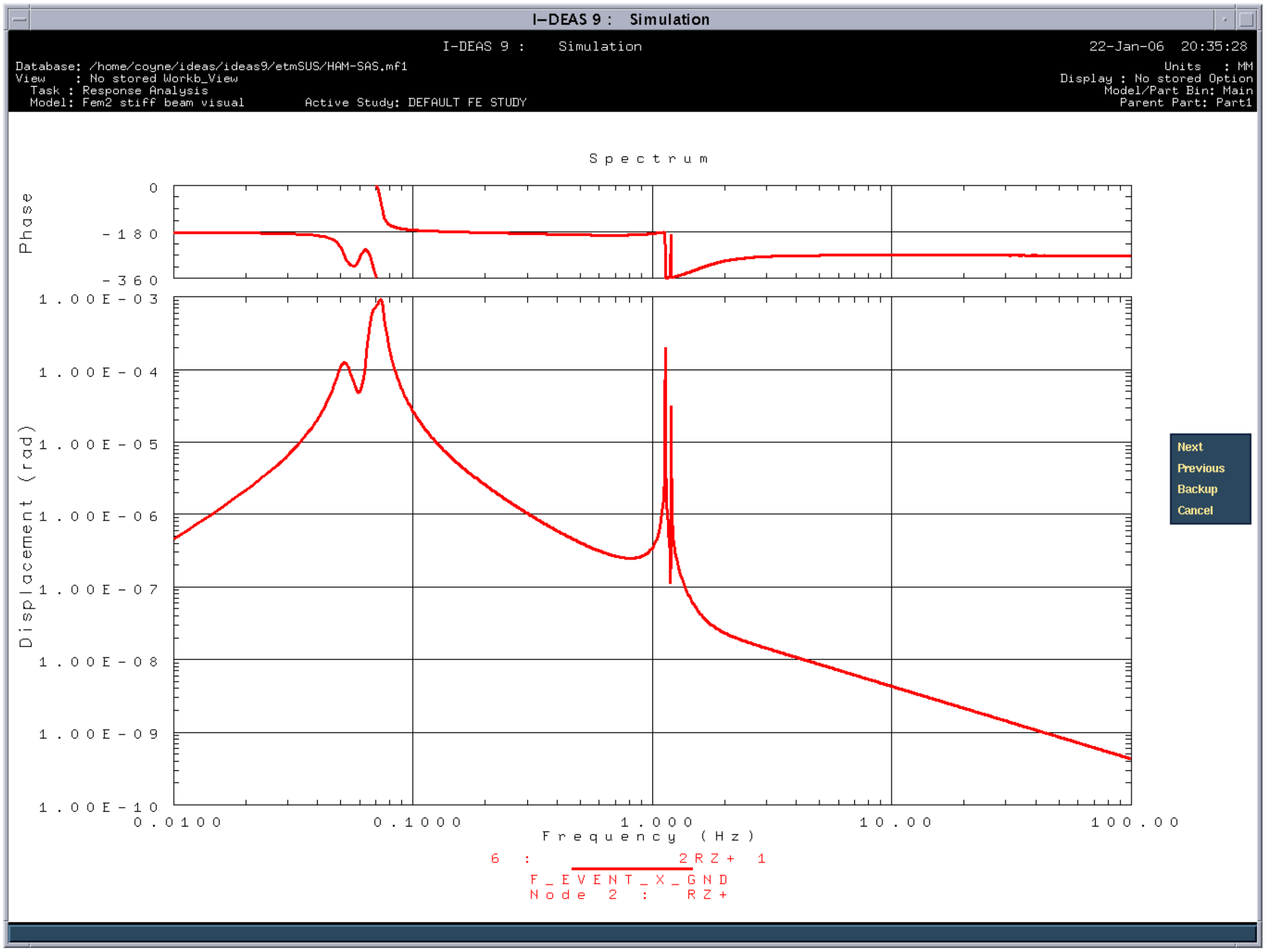
```
I-DEAS 9 :     Simulation                                   22-Jan-06   20:35:05
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                Units   : MM
View    : No stored Workb_View                           Display : No stored Option
  Task : Response Analysis                                  Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY   Parent Part: Part1
```



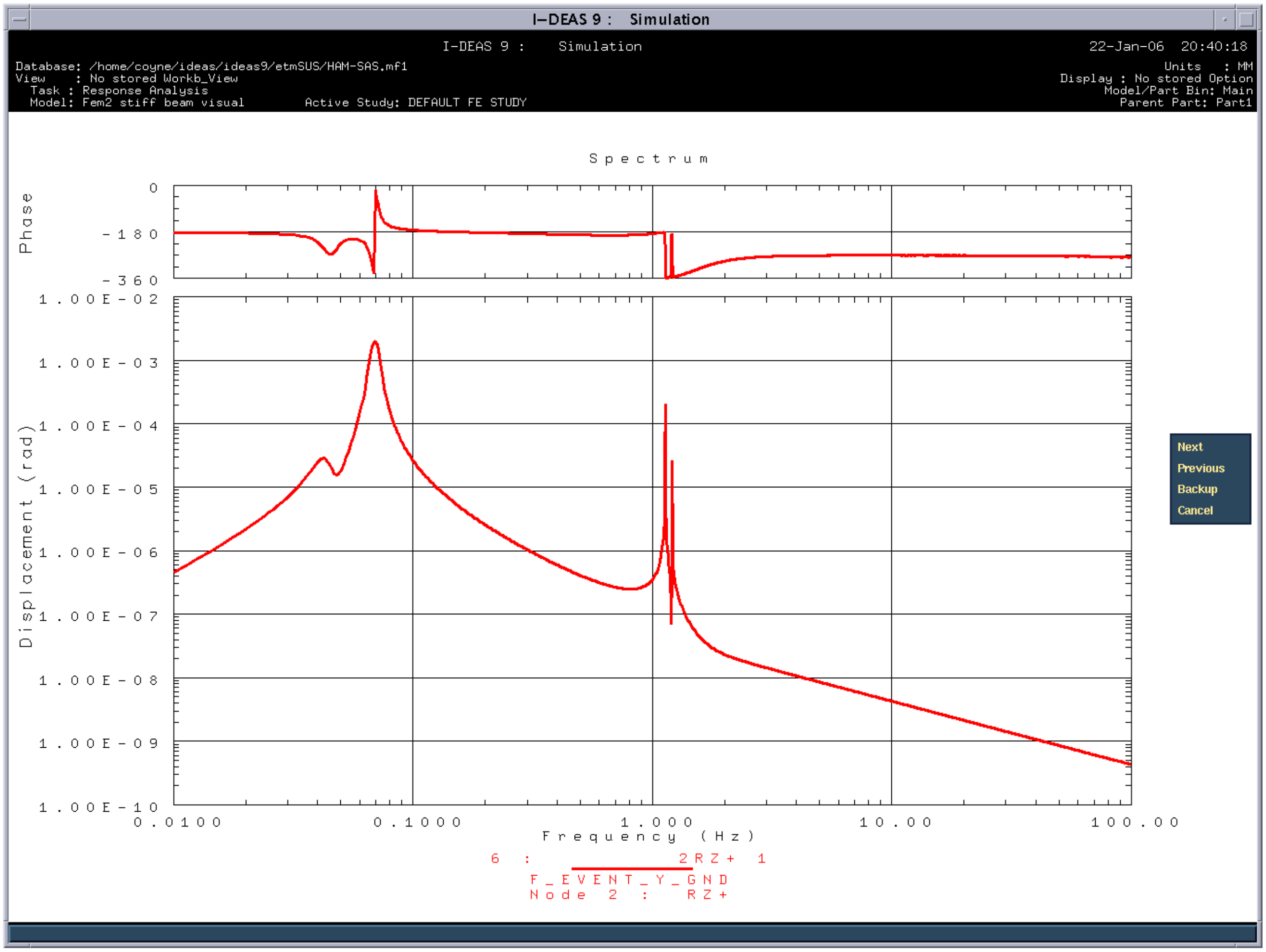
```
I-DEAS 9 :     Simulation                                22-Jan-06  20:35:13
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                   Units    : MM
View    : No stored Workb_View                           Display : No stored Option
  Task : Response Analysis                                   Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY      Parent Part: Part1
```



```
I-DEAS 9 :     Simulation                                            22-Jan-06   20:35:21
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                            Units    : MM
View    : No stored Workb_View                                     Display : No stored Option
  Task  : Response Analysis                                          Model/Part Bin: Main
  Model: Fem2 stiff beam visual       Active Study: DEFAULT FE STUDY      Parent Part: Part1
```

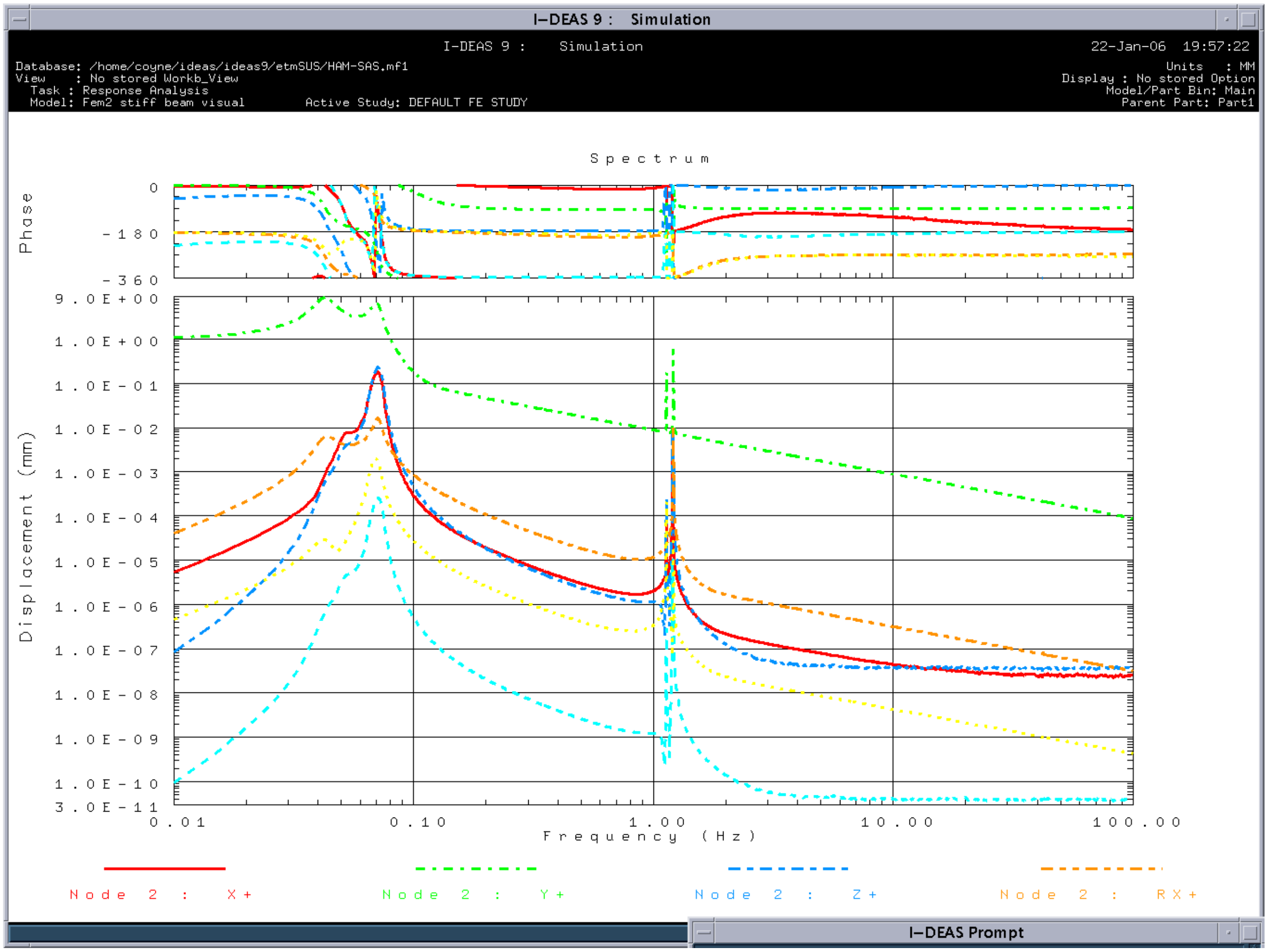


```
I-DEAS 9 :     Simulation                                   22-Jan-06   20:35:28
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                Units    : MM
View     : No stored Workb_View                        Display : No stored Option
  Task : Response Analysis                                  Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY        Parent Part: Part1
```

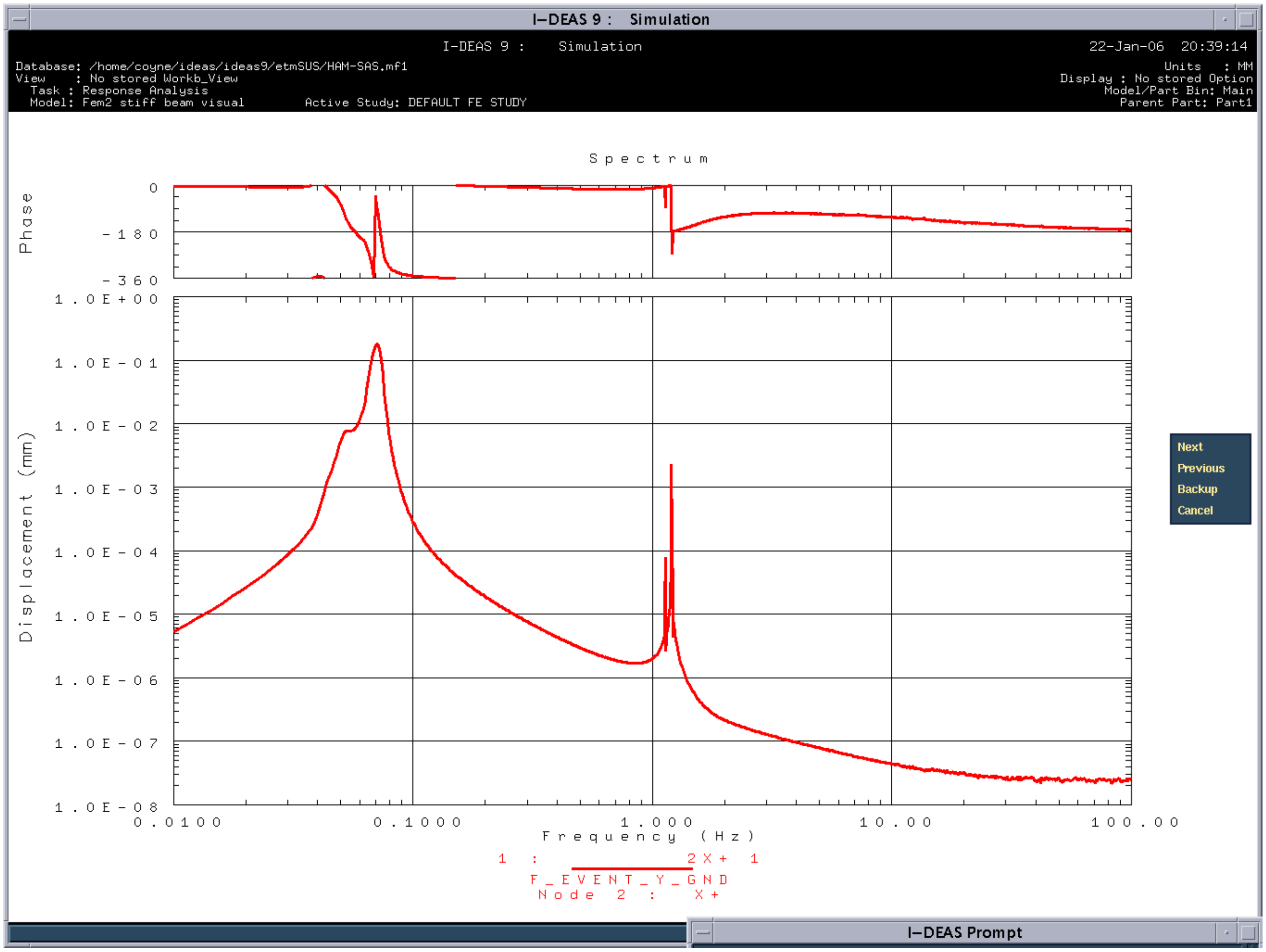


```
I-DEAS 9 :     Simulation                                22-Jan-06  20:40:18
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1           Units   : MM
View    : No stored Workb_View                   Display : No stored Option
  Task : Response Analysis                        Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY        Parent Part: Part1
```

Figure 23: Y Ground Motion to Suspension Point Motion

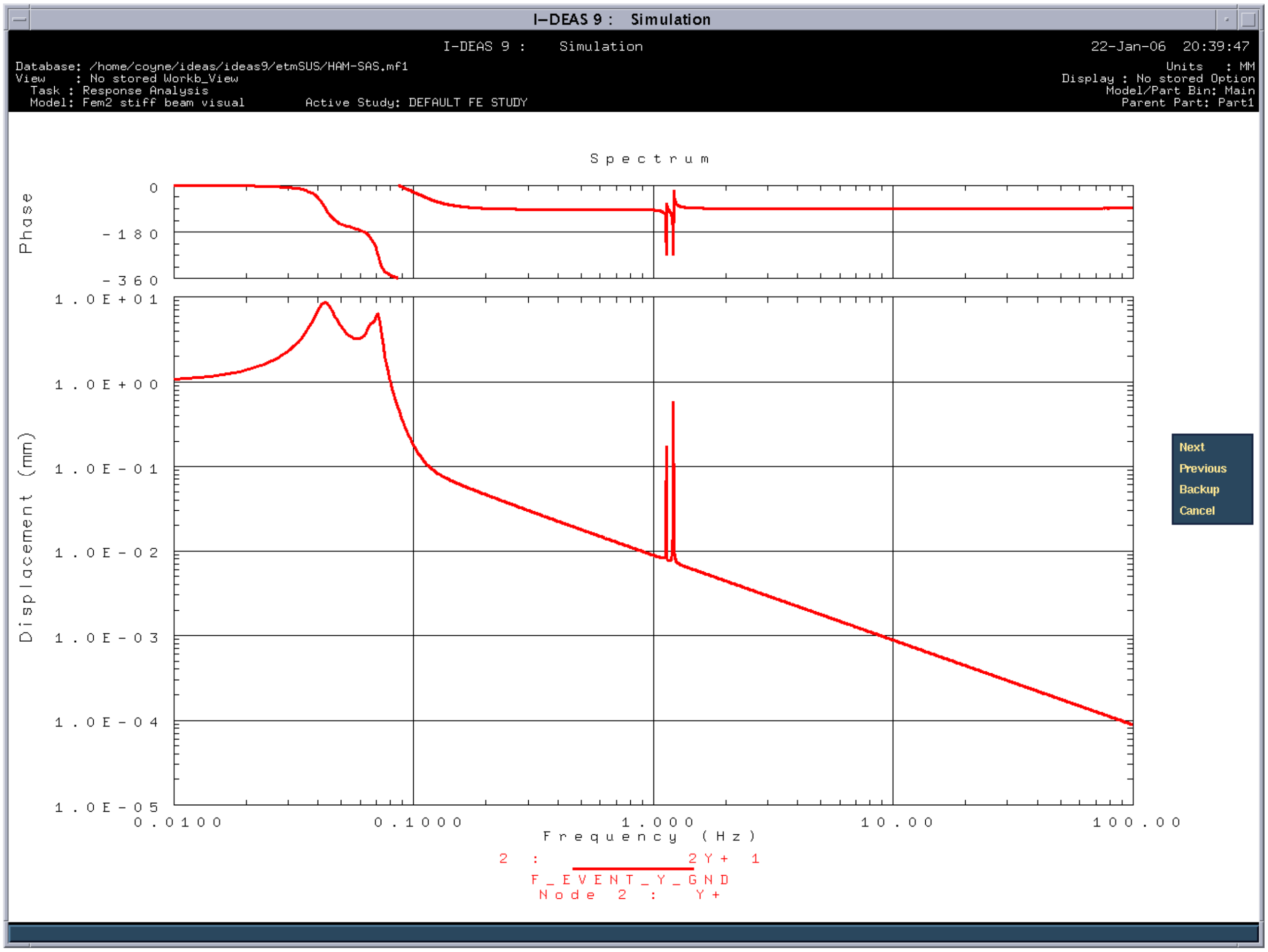


```
                         I-DEAS 9 :    Simulation                          22-Jan-06  19:57:22
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                            Units   : MM
View    : No stored Workb_View                                        Display : No stored Option
 Task : Response Analysis                                                   Model/Part Bin: Main
 Model: Fem2 stiff beam visual         Active Study: DEFAULT FE STUDY        Parent Part: Part1
```

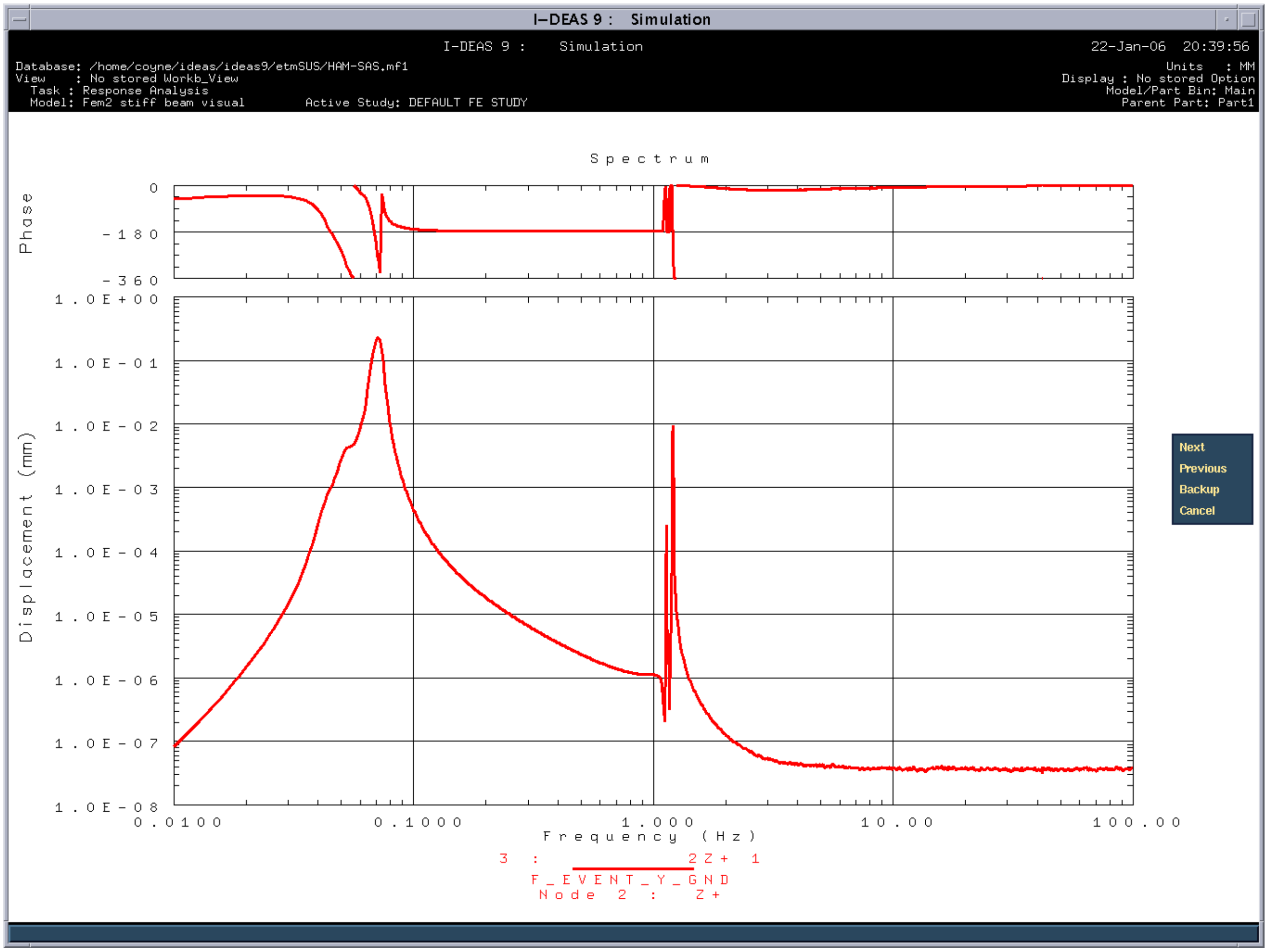


I-DEAS 9 : Simulation 22-Jan-06 20:39:14

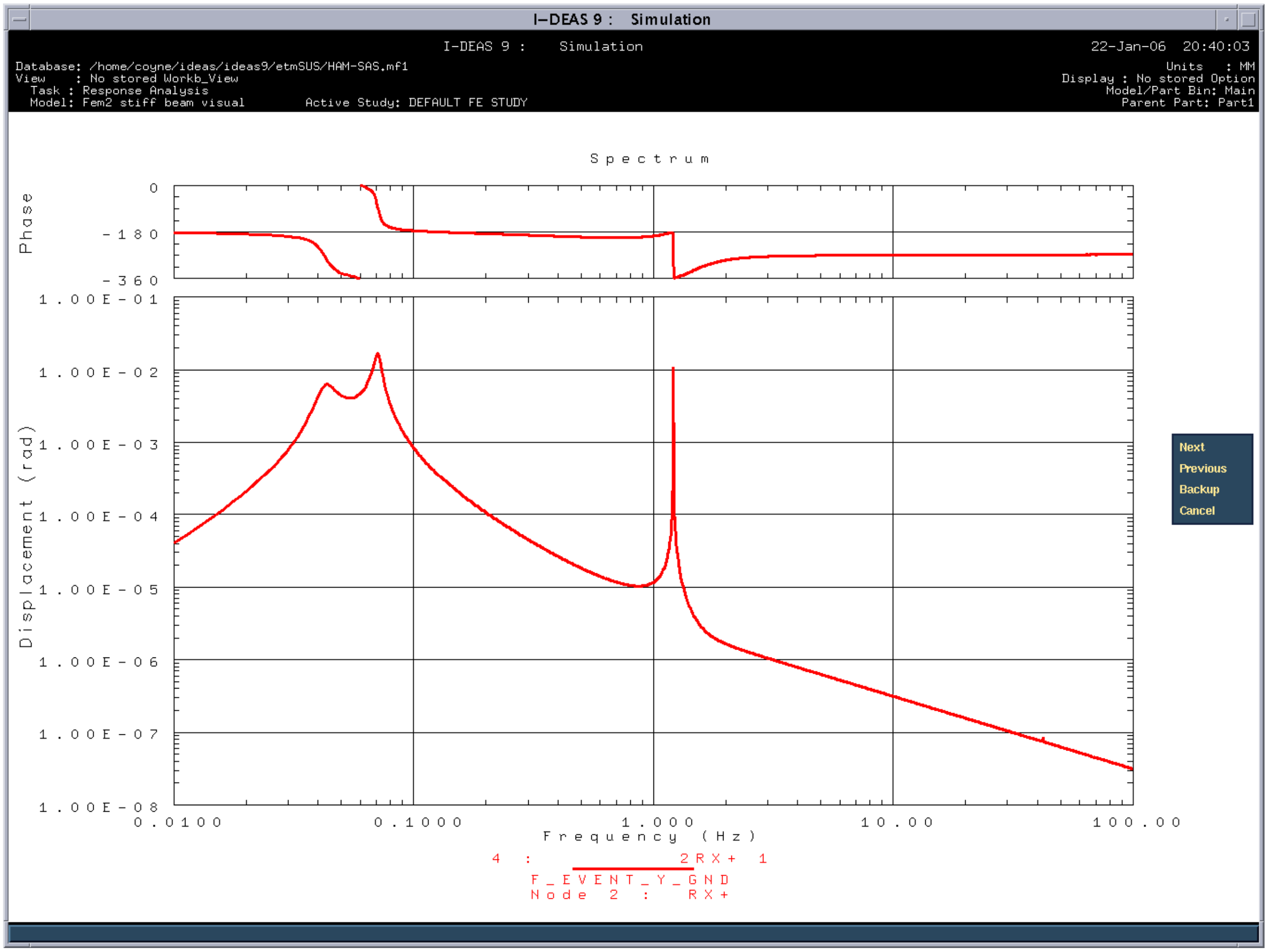
```
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                  Units    : MM
View    : No stored Workb_View                              Display : No stored Option
  Task : Response Analysis                                   Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY     Parent Part: Part1
```



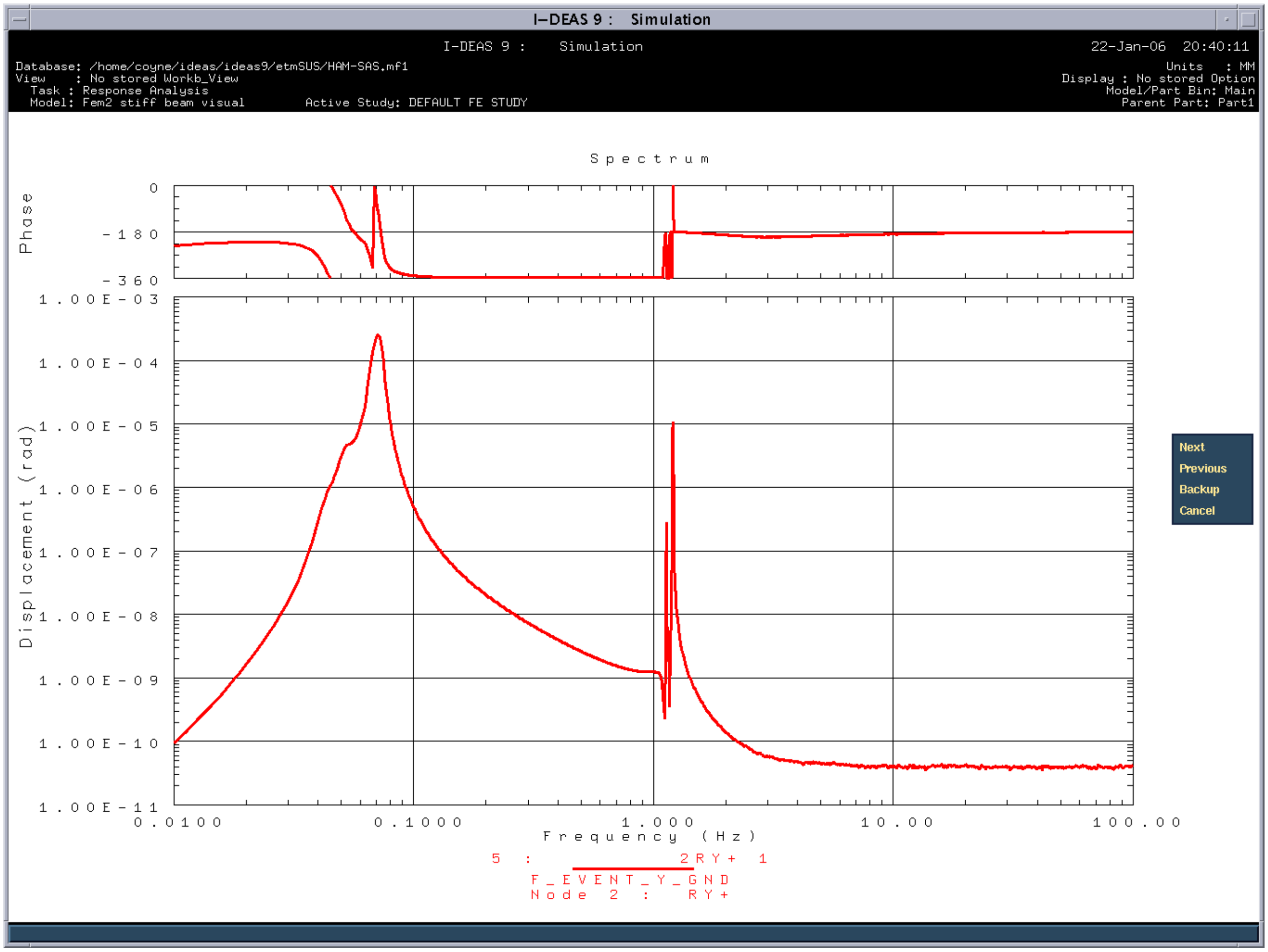
```
I-DEAS 9 :     Simulation                                  22-Jan-06   20:39:47
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                Units    : MM
View     : No stored Workb_View                        Display : No stored Option
  Task : Response Analysis                                   Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY    Parent Part: Part1
```



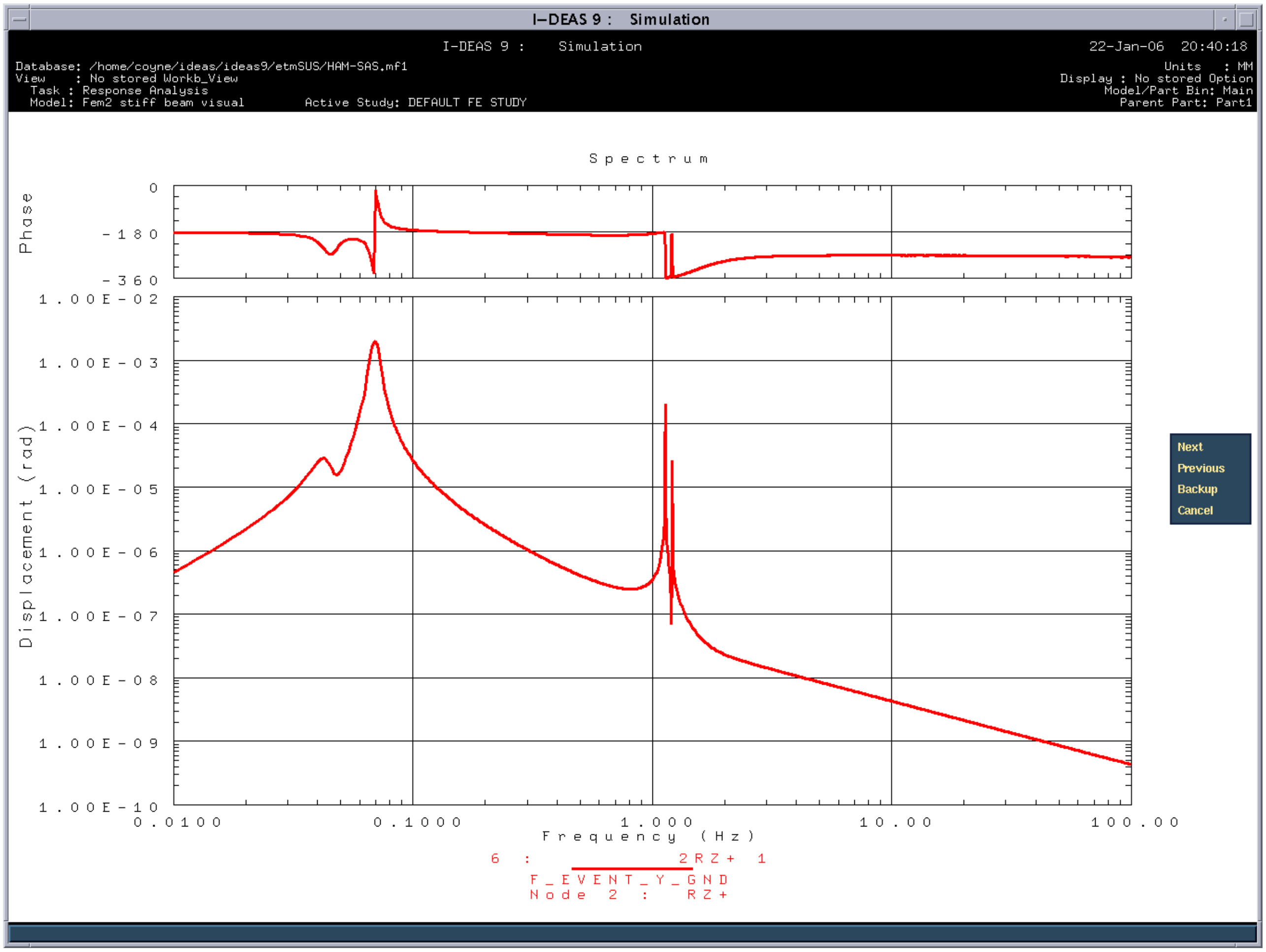
```
I-DEAS 9 :   Simulation
                  I-DEAS 9 :     Simulation                              22-Jan-06   20:39:56
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                         Units   : MM
View    : No stored Workb_View                                      Display : No stored Option
  Task : Response Analysis                                               Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY        Parent Part: Part1
```



```
I-DEAS 9 :    Simulation                                  22-Jan-06  20:40:03
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                  Units   : MM
View    : No stored Workb_View                            Display : No stored Option
  Task : Response Analysis                                      Model/Part Bin: Main
  Model: Fem2 stiff beam visual      Active Study: DEFAULT FE STUDY      Parent Part: Part1
```

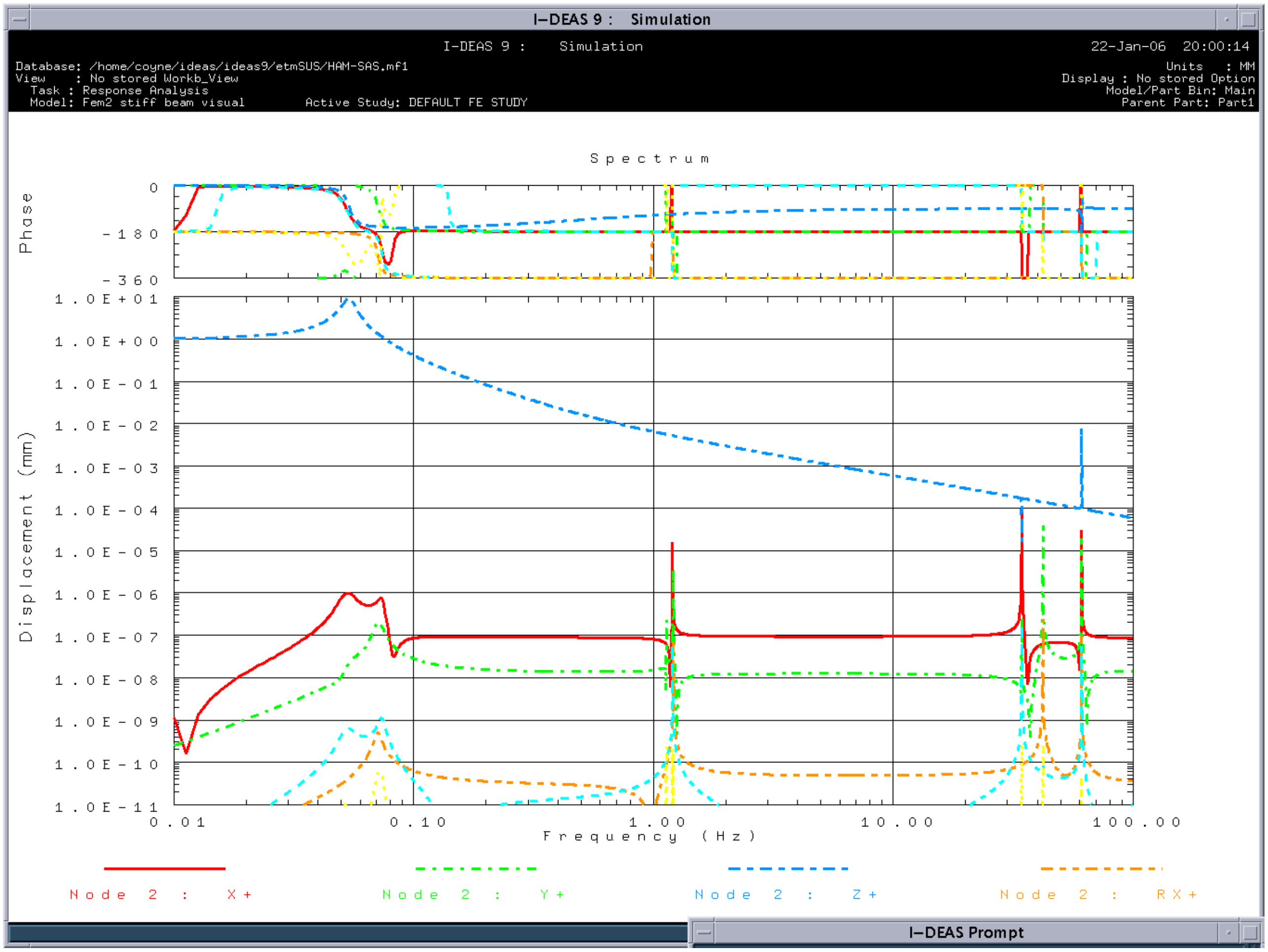


```
I-DEAS 9 :     Simulation                                  22-Jan-06  20:40:11
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                 Units   : MM
View    : No stored Workb_View                           Display : No stored Option
  Task : Response Analysis                                  Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY       Parent Part: Part1
```

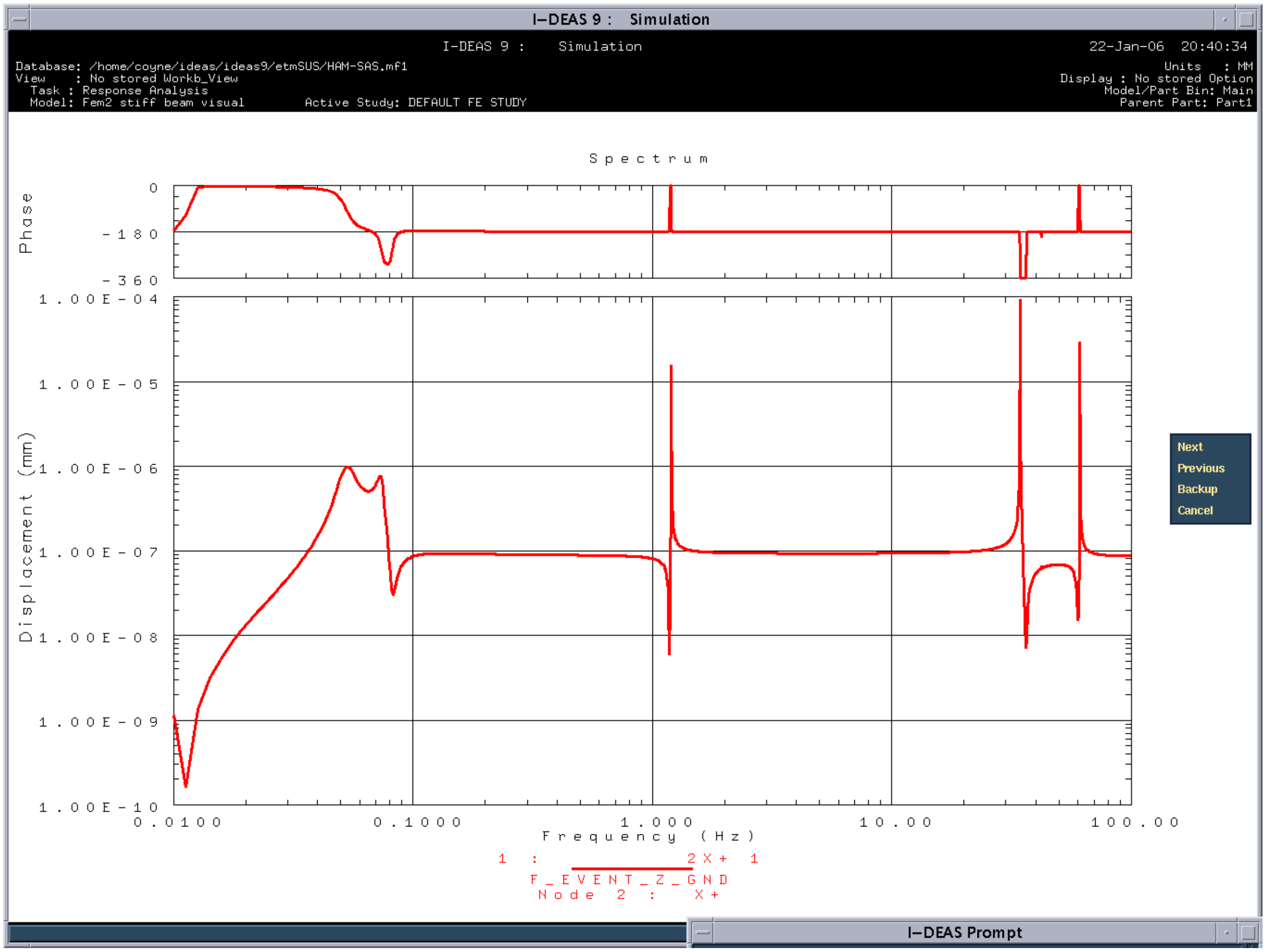


```
I-DEAS 9 :     Simulation                                  22-Jan-06  20:40:18
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                 Units    : MM
View    : No stored Workb_View                            Display : No stored Option
  Task : Response Analysis                                   Model/Part Bin: Main
  Model: Fem2 stiff beam visual       Active Study: DEFAULT FE STUDY      Parent Part: Part1
```

Figure 24: Z Ground Motion to Suspension Point Motion



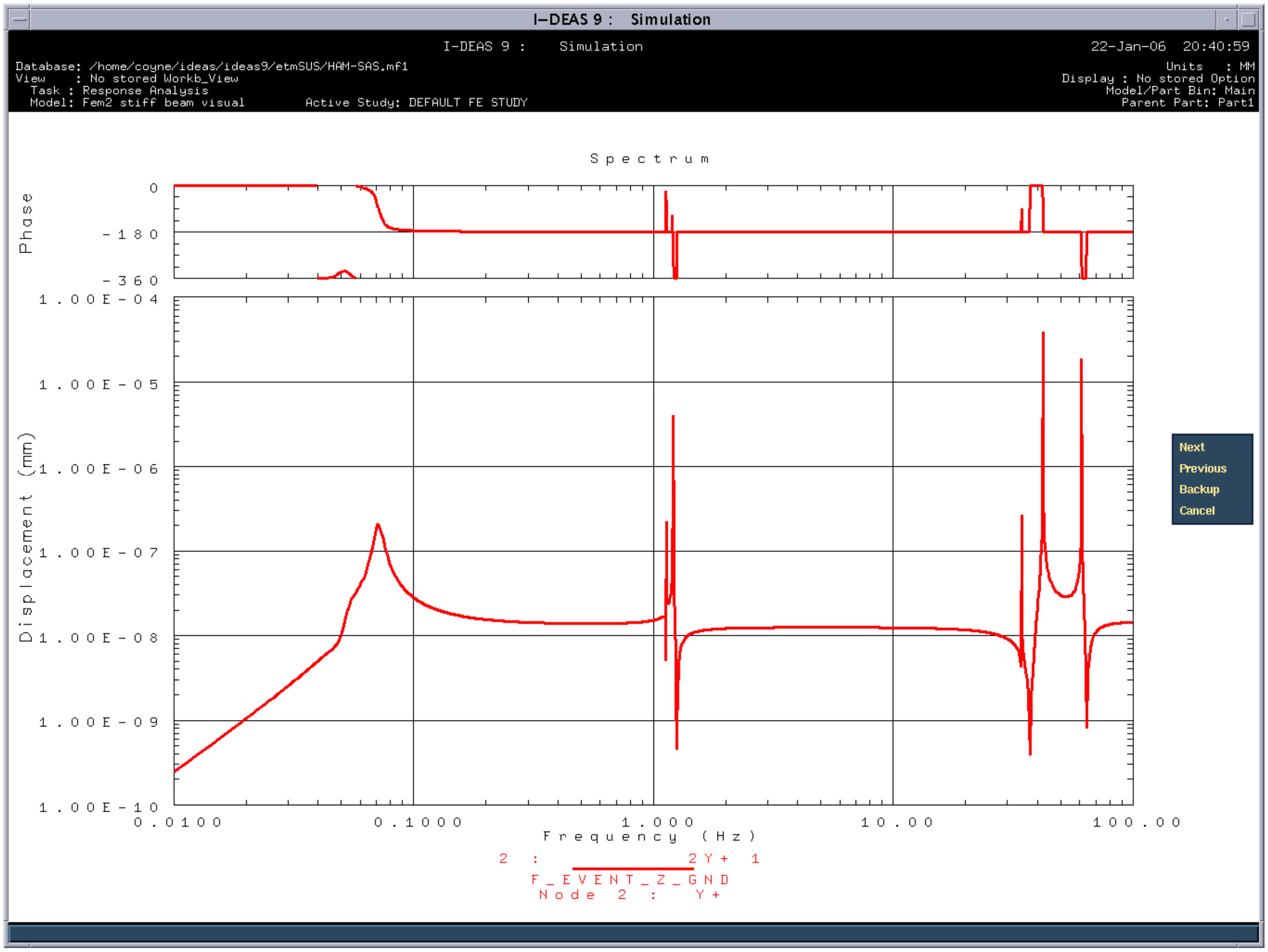
```
I-DEAS 9 :     Simulation                                22-Jan-06  20:00:14
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                Units    : MM
View     : No stored Workb_View                          Display : No stored Option
  Task : Response Analysis                                      Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY     Parent Part: Part1
```



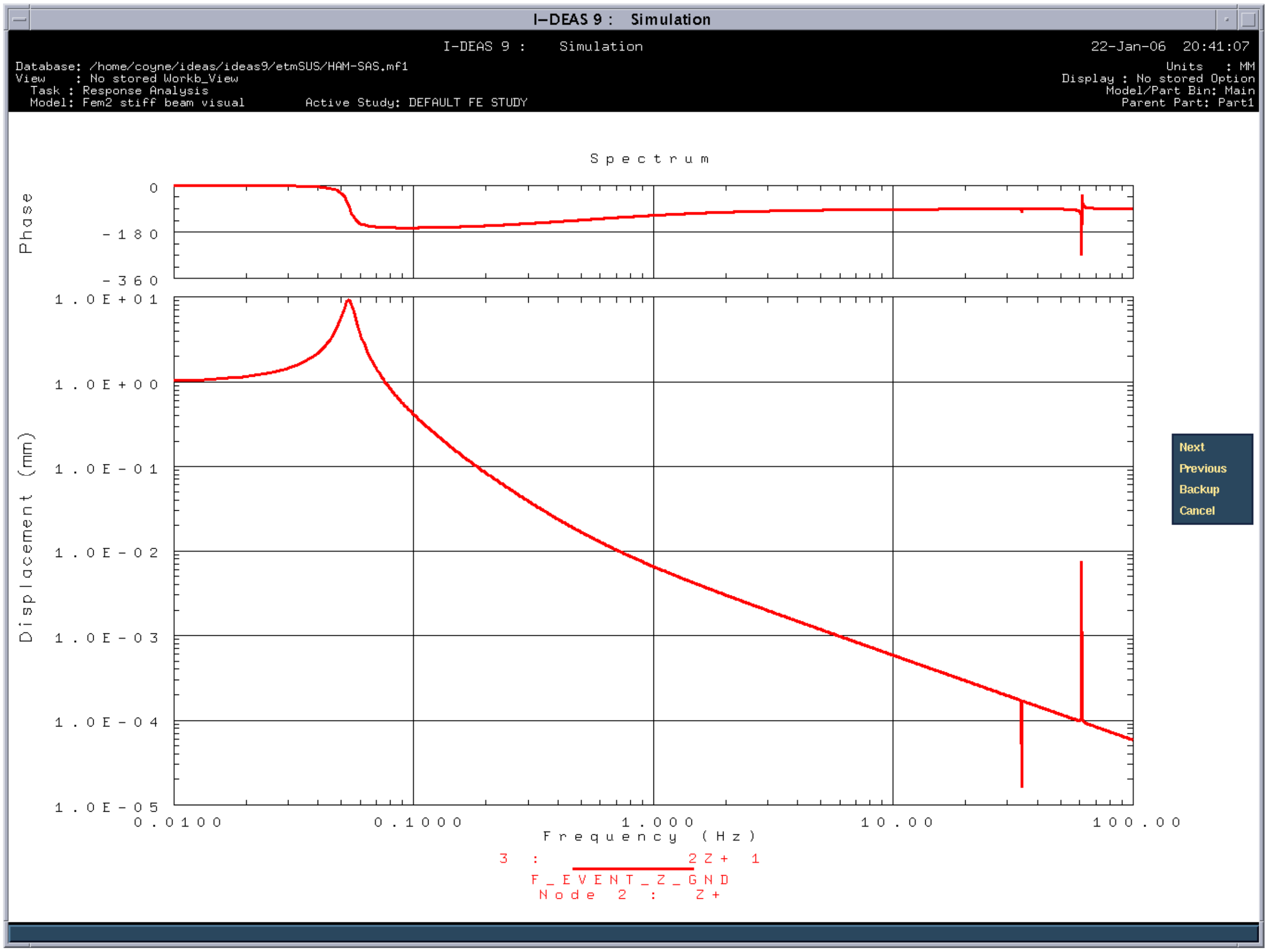
I-DEAS 9 : Simulation

I-DEAS 9 : Simulation 22-Jan-06 20:40:34

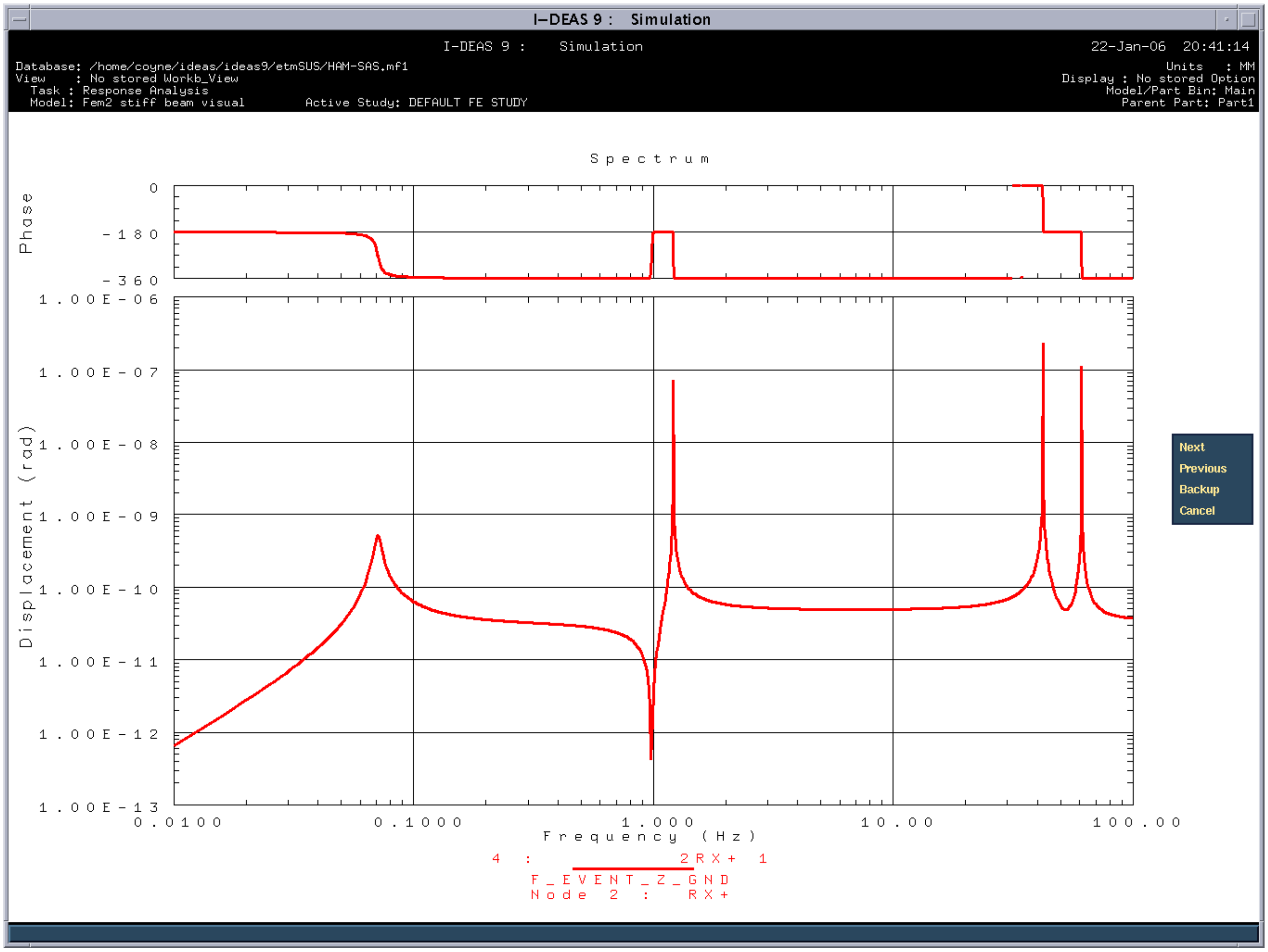
```
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1              Units   : MM
View    : No stored Workb_View                          Display : No stored Option
  Task  : Response Analysis                                 Model/Part Bin: Main
  Model: Fem2 stiff beam visual     Active Study: DEFAULT FE STUDY     Parent Part: Part1
```



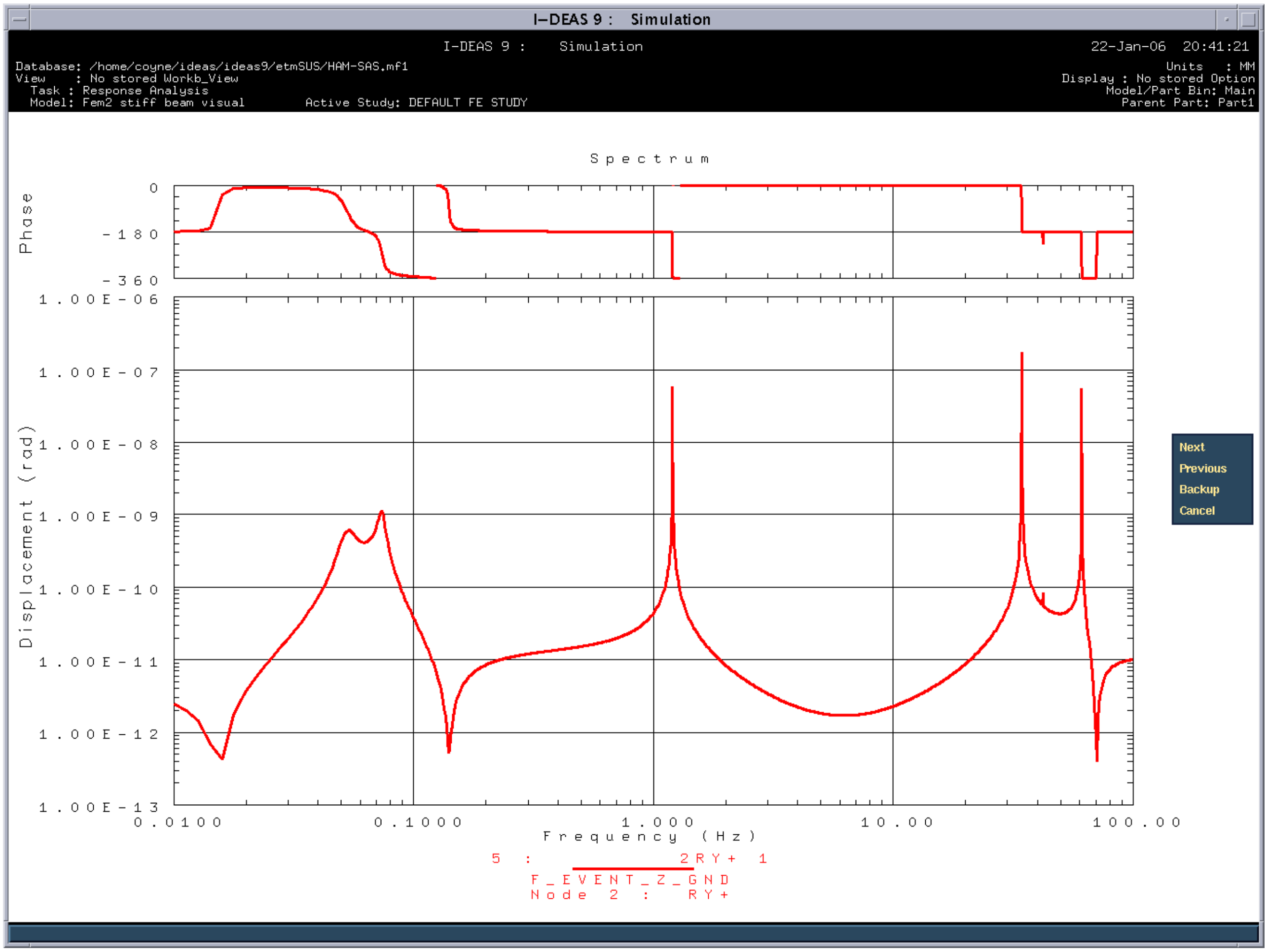
```
I-DEAS 9 :    Simulation                                         22-Jan-06   20:40:59
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                          Units    : MM
View    : No stored Workb_View                                    Display : No stored Option
  Task : Response Analysis                                          Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY        Parent Part: Part1
```



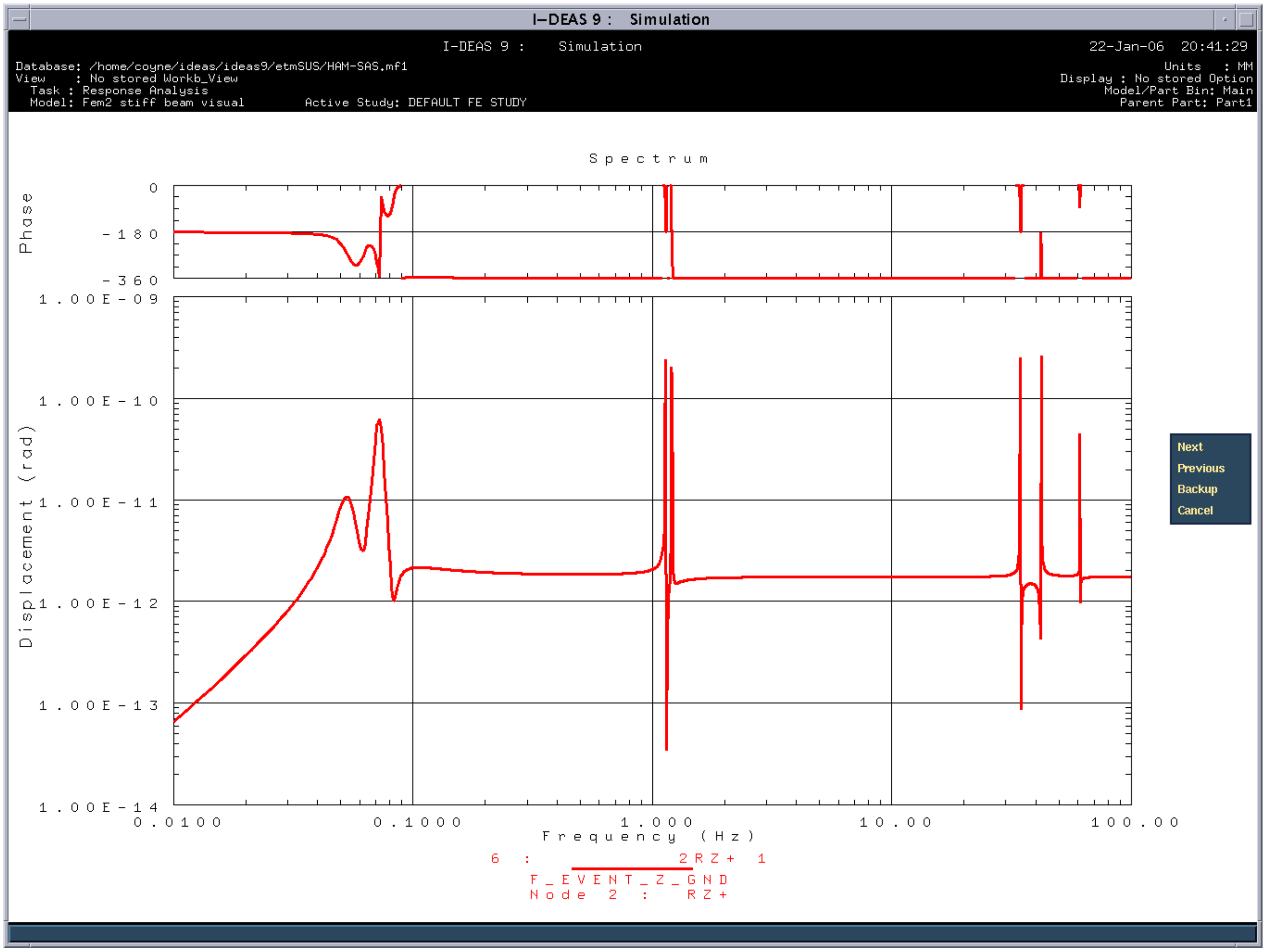
```
                              I-DEAS 9 :    Simulation                              22-Jan-06   20:41:07
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                                       Units   : MM
View    : No stored Workb_View                                               Display : No stored Option
  Task : Response Analysis                                                       Model/Part Bin: Main
  Model: Fem2 stiff beam visual         Active Study: DEFAULT FE STUDY              Parent Part: Part1
```



```
I-DEAS 9 :     Simulation                                    22-Jan-06  20:41:14
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                  Units    : MM
View     : No stored Workb_View                          Display : No stored Option
  Task : Response Analysis                                 Model/Part Bin: Main
  Model: Fem2 stiff beam visual       Active Study: DEFAULT FE STUDY    Parent Part: Part1
```



```
I-DEAS 9 :     Simulation                                  22-Jan-06  20:41:21
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                  Units    : MM
View     : No stored Workb_View                         Display : No stored Option
  Task : Response Analysis                                  Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY     Parent Part: Part1
```



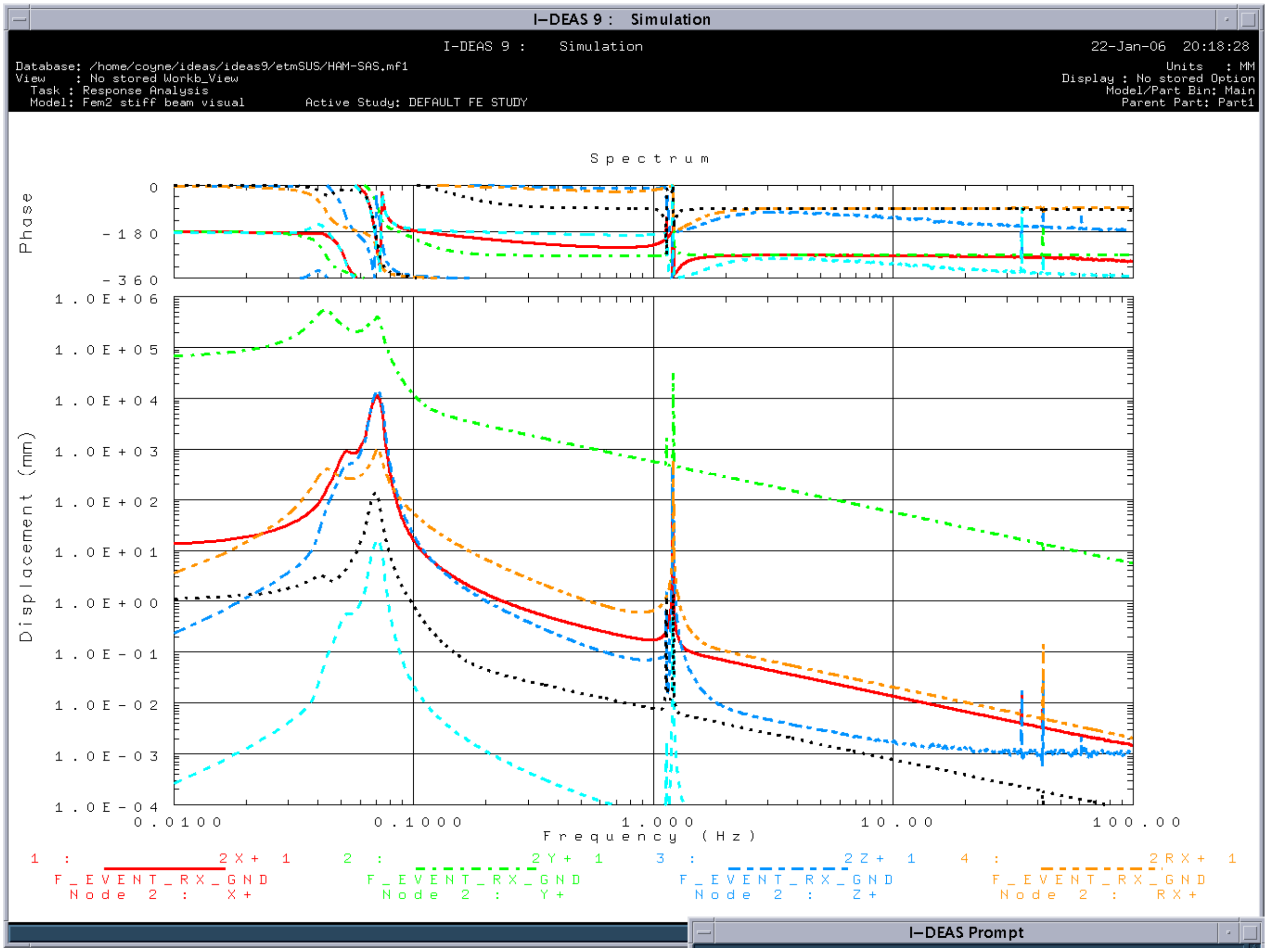
I–DEAS 9 : Simulation

I-DEAS 9 : Simulation 22-Jan-06 20:41:29

Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1
View : No stored Workb_View
Task : Response Analysis
Model: Fem2 stiff beam visual Active Study: DEFAULT FE STUDY

Units : MM
Display : No stored Option
Model/Part Bin: Main
Parent Part: Part1

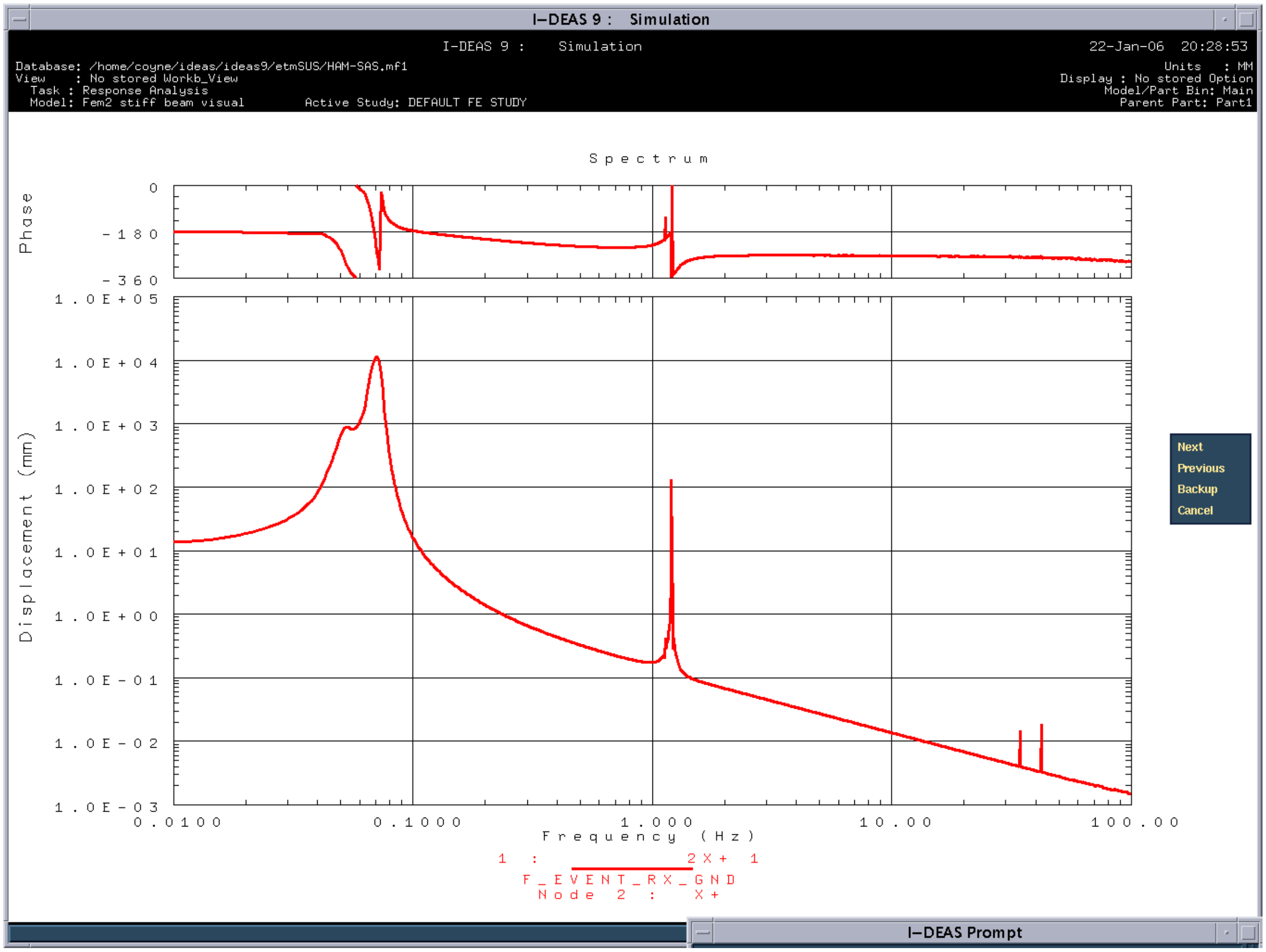
Figure 25: RX Ground Motion to Suspension Point Motion



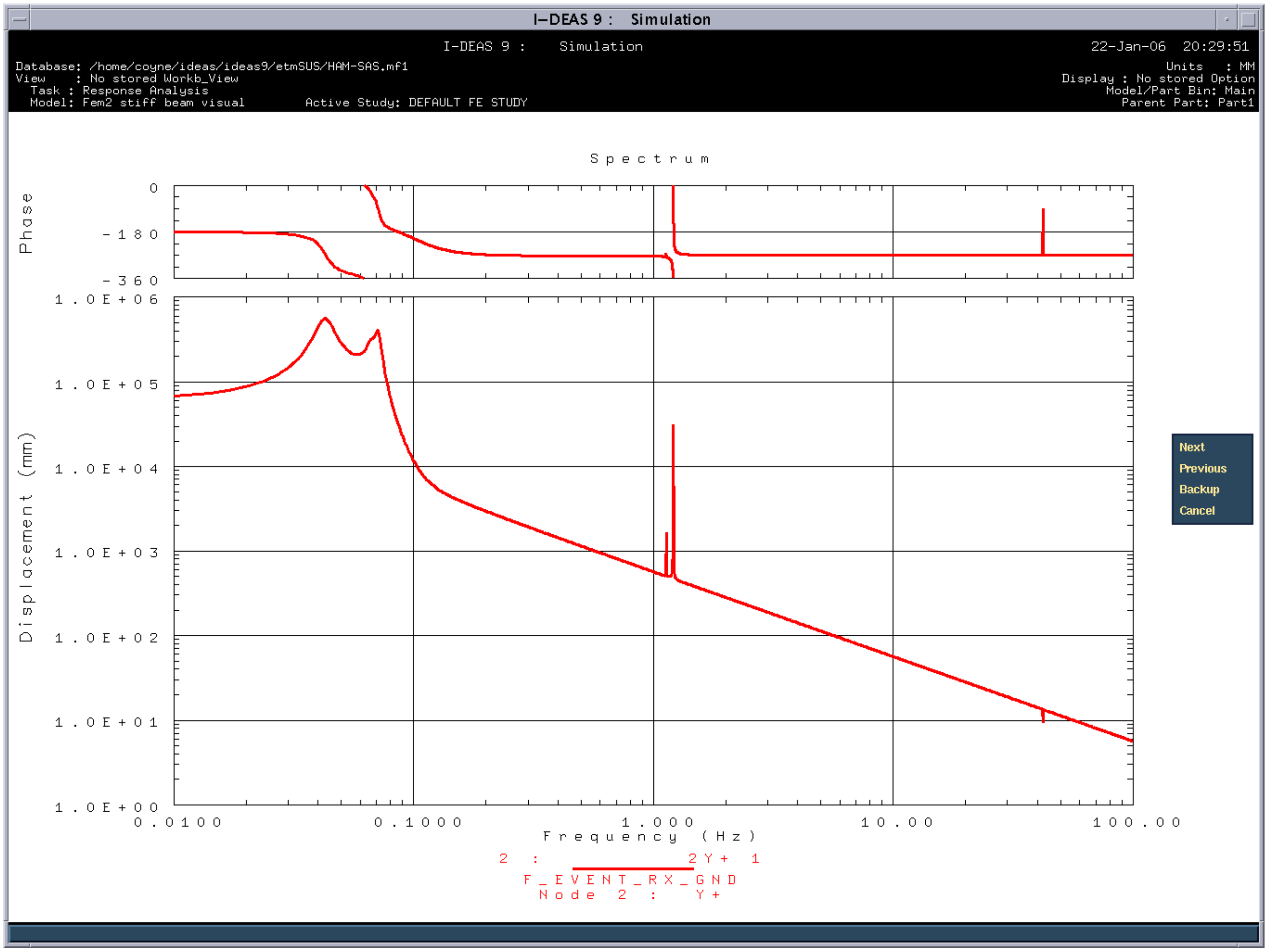
I-DEAS 9 : Simulation 22-Jan-06 20:18:28

Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1
View : No stored Workb_View
Task : Response Analysis
Model: Fem2 stiff beam visual
Active Study: DEFAULT FE STUDY

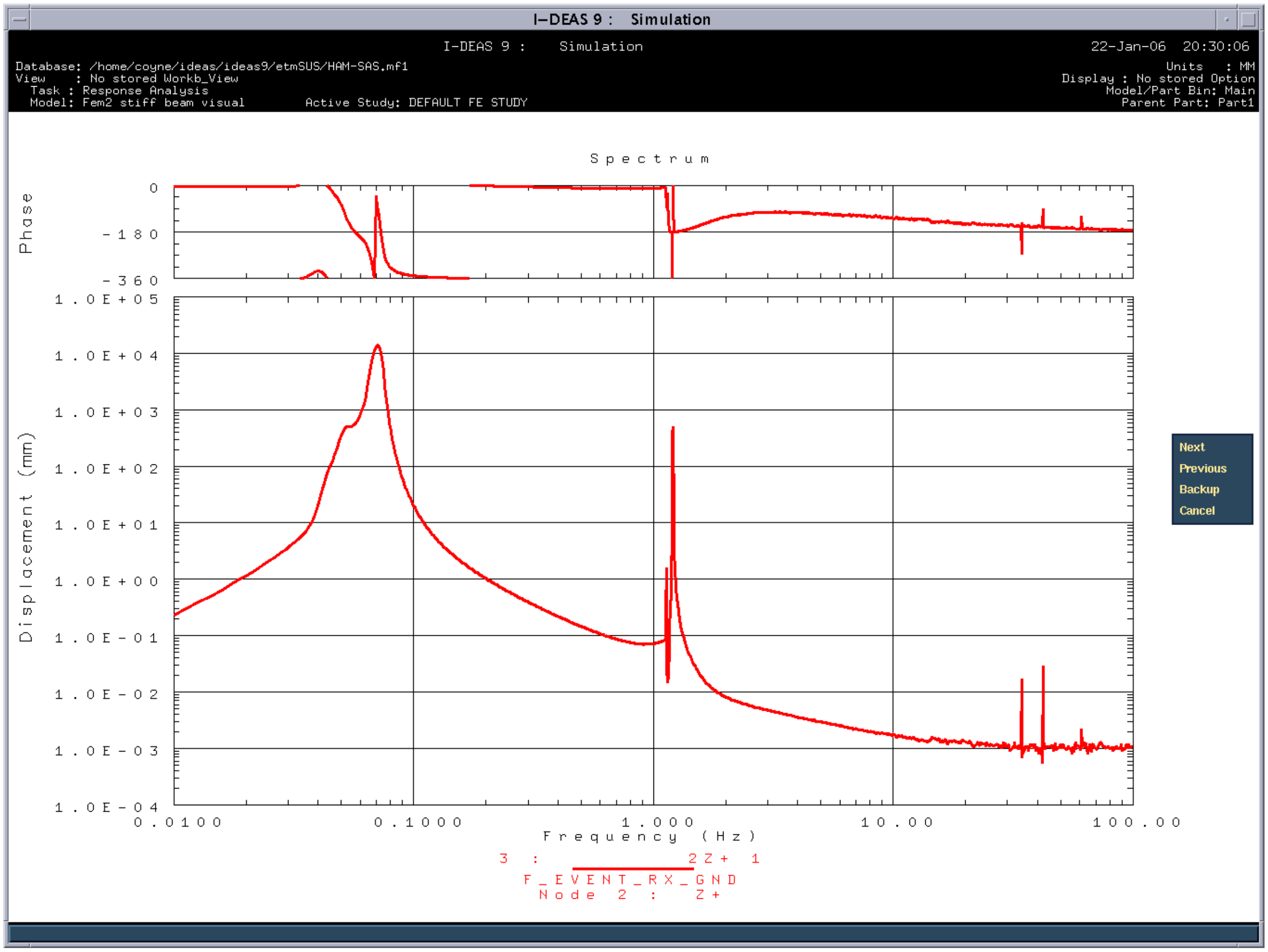
Units : MM
Display : No stored Option
Model/Part Bin: Main
Parent Part: Part1



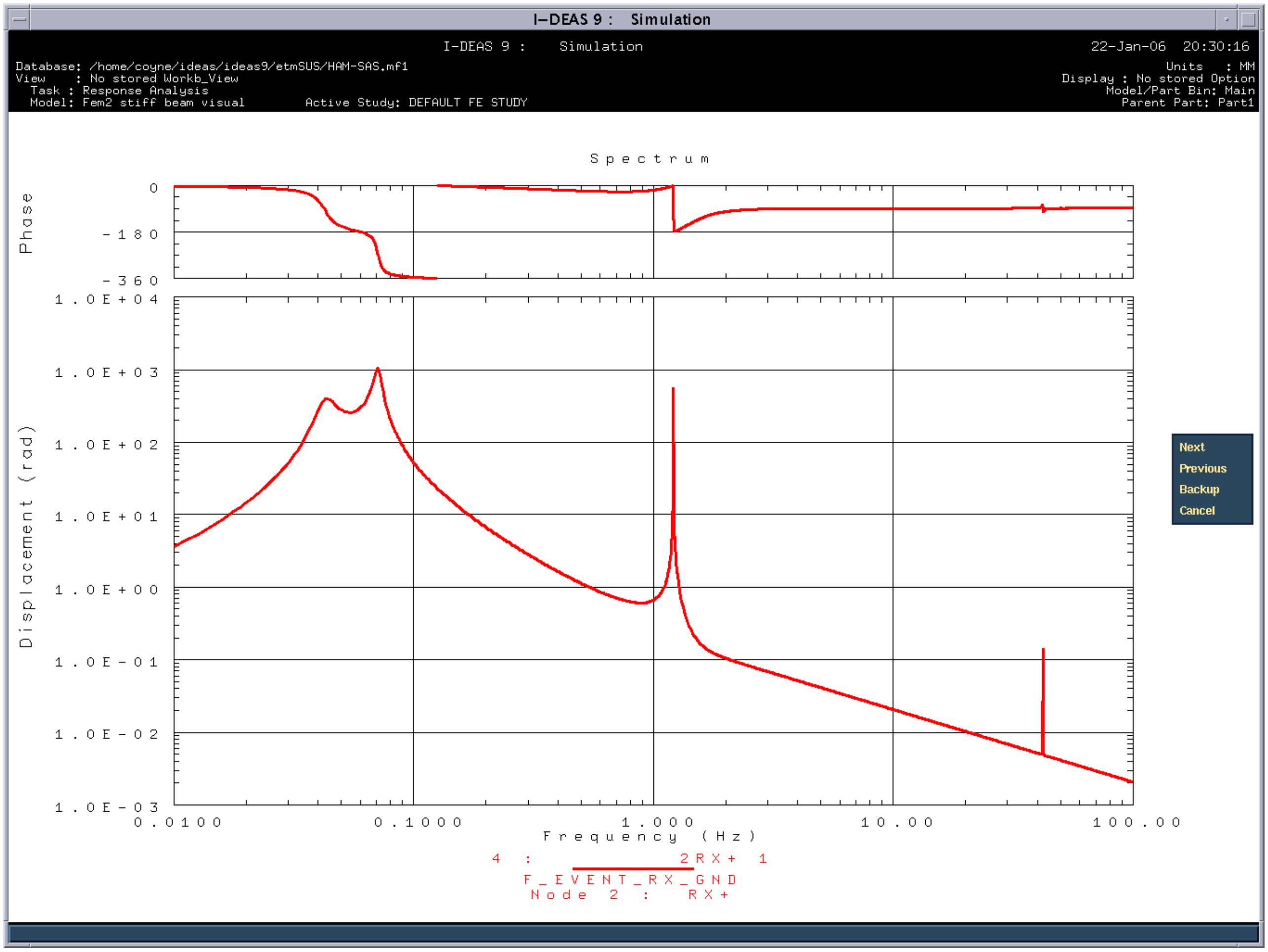
```
I-DEAS 9 :    Simulation                                   22-Jan-06   20:28:53
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                    Units   : MM
View    : No stored Workb_View                                Display : No stored Option
  Task : Response Analysis                                     Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY      Parent Part: Part1
```



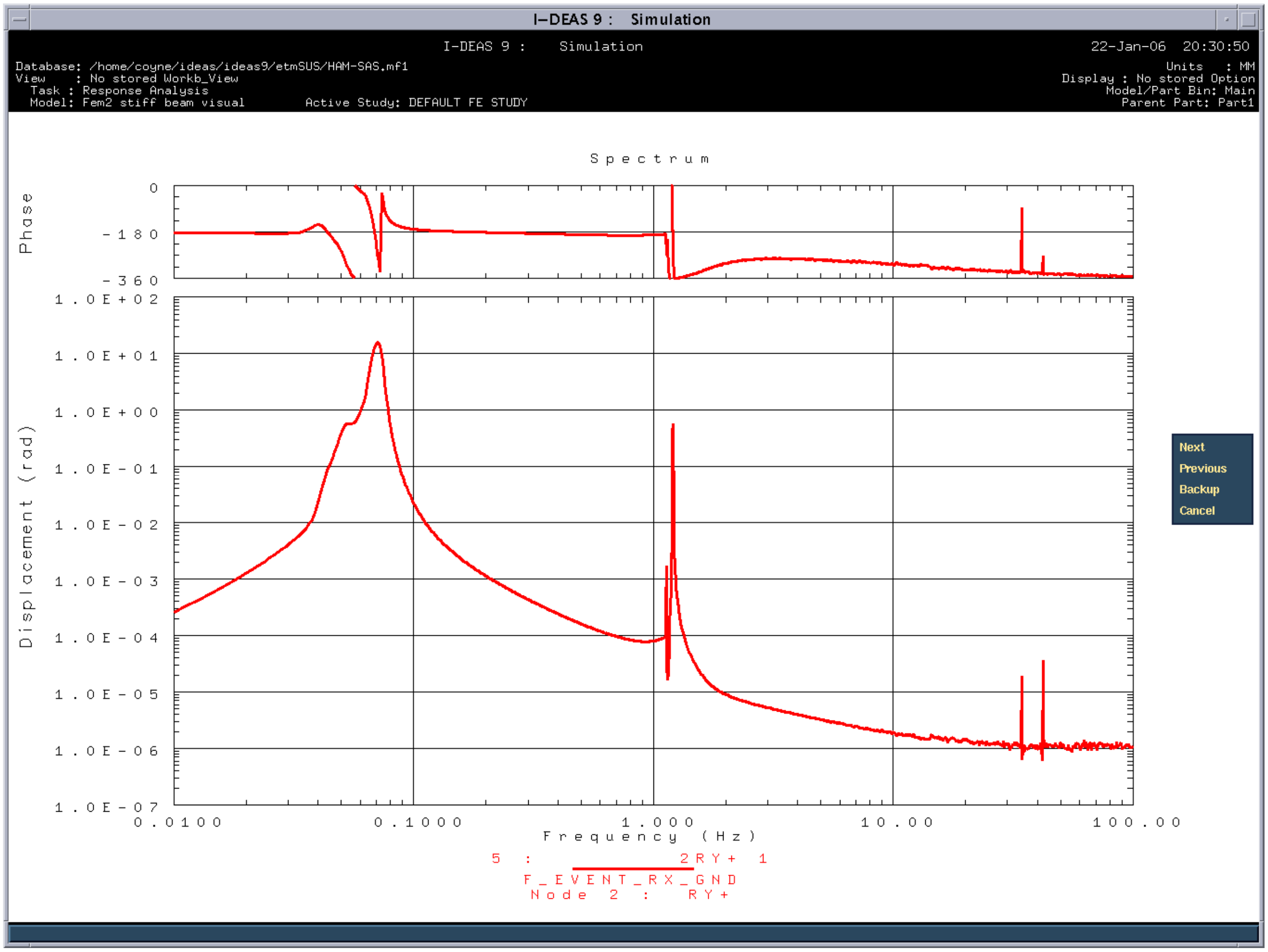
```
I-DEAS 9 :    Simulation                                   22-Jan-06   20:29:51
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                Units   : MM
View    : No stored Workb_View                       Display : No stored Option
  Task : Response Analysis                               Model/Part Bin: Main
  Model: Fem2 stiff beam visual       Active Study: DEFAULT FE STUDY     Parent Part: Part1
```



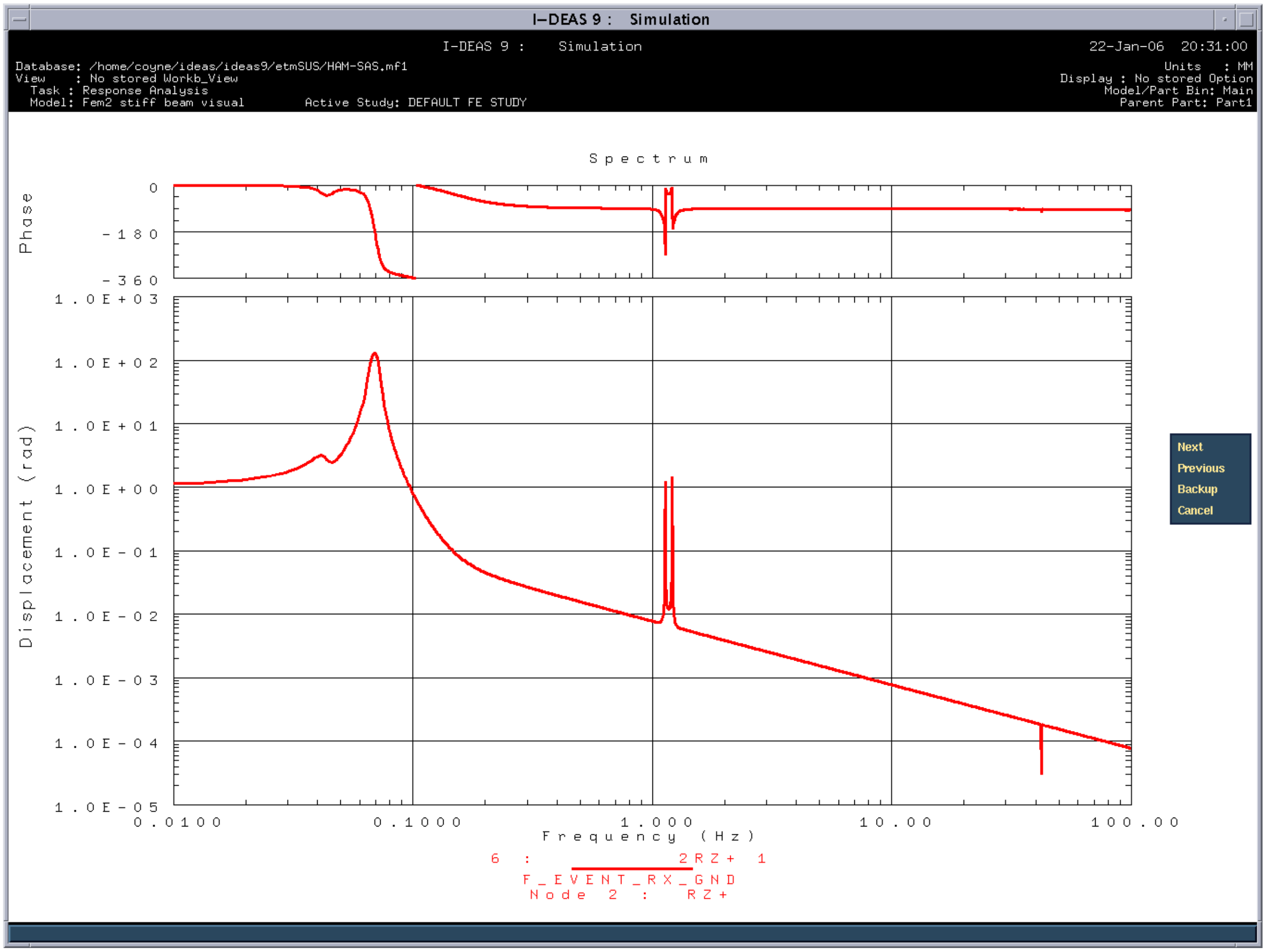
```
I-DEAS 9 :    Simulation                                22-Jan-06   20:30:06
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                Units   : MM
View    : No stored Workb_View                         Display : No stored Option
  Task : Response Analysis                               Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY   Parent Part: Part1
```



```
I-DEAS 9 :    Simulation                                         22-Jan-06   20:30:16
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                     Units    : MM
View    : No stored Workb_View                                 Display : No stored Option
  Task : Response Analysis                                          Model/Part Bin: Main
  Model: Fem2 stiff beam visual         Active Study: DEFAULT FE STUDY    Parent Part: Part1
```

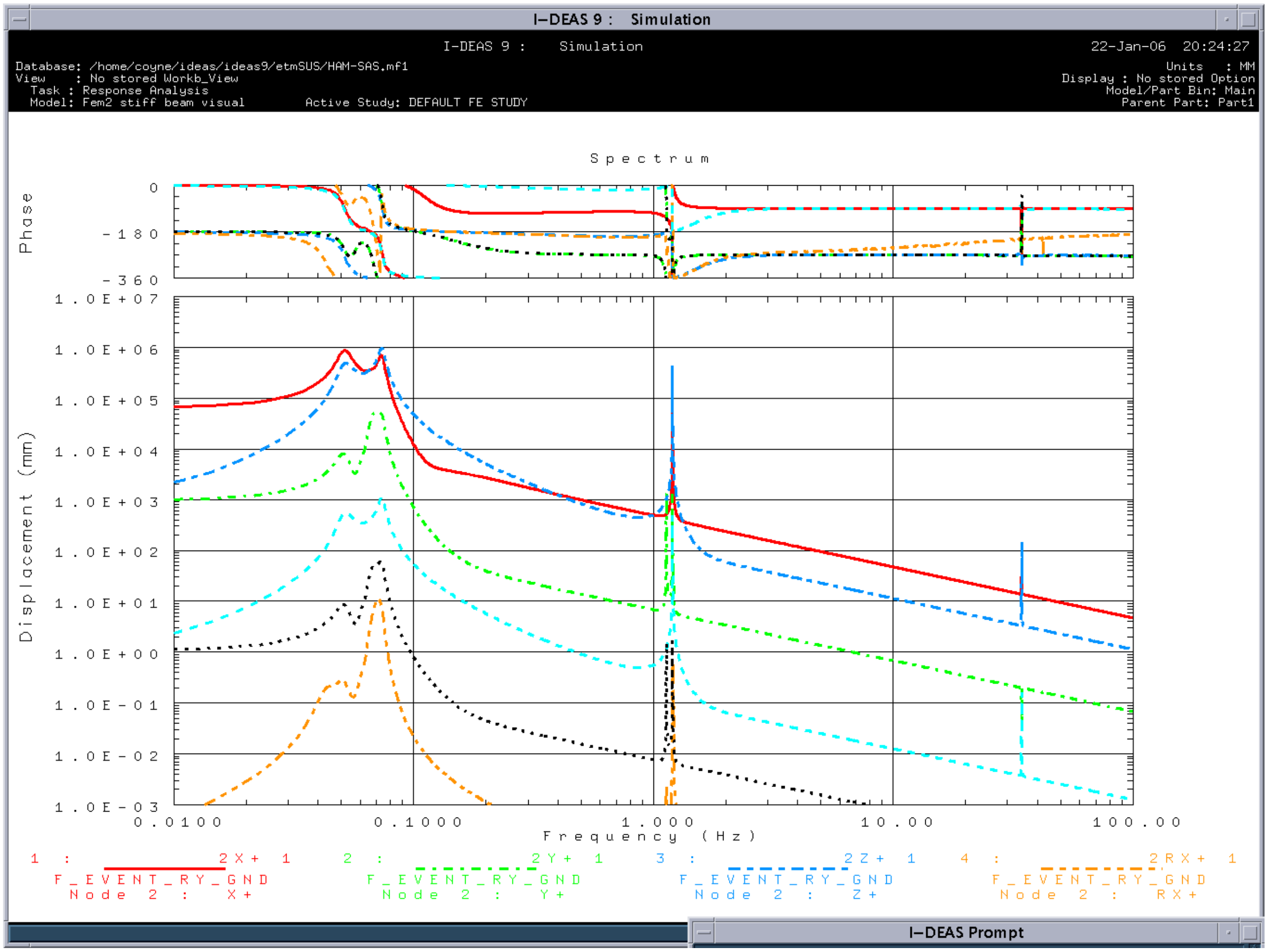


```
I-DEAS 9 :    Simulation                                         22-Jan-06   20:30:50
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                 Units   : MM
View    : No stored Workb_View                             Display : No stored Option
  Task : Response Analysis                                      Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY   Parent Part: Part1
```

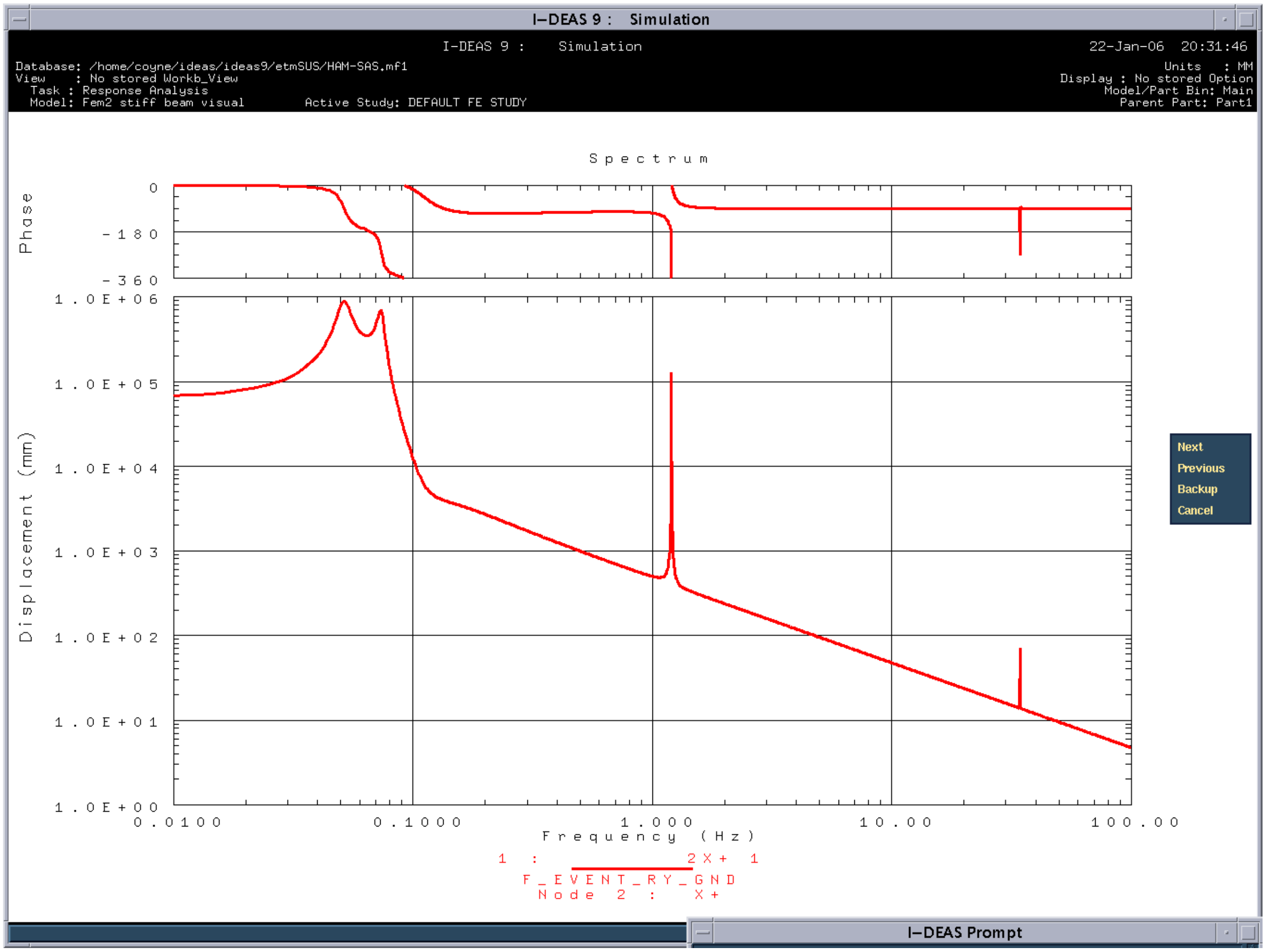


```
I-DEAS 9 :    Simulation                                   22-Jan-06  20:31:00
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                  Units   : MM
View    : No stored Workb_View                             Display : No stored Option
  Task : Response Analysis                                      Model/Part Bin: Main
  Model: Fem2 stiff beam visual       Active Study: DEFAULT FE STUDY      Parent Part: Part1
```

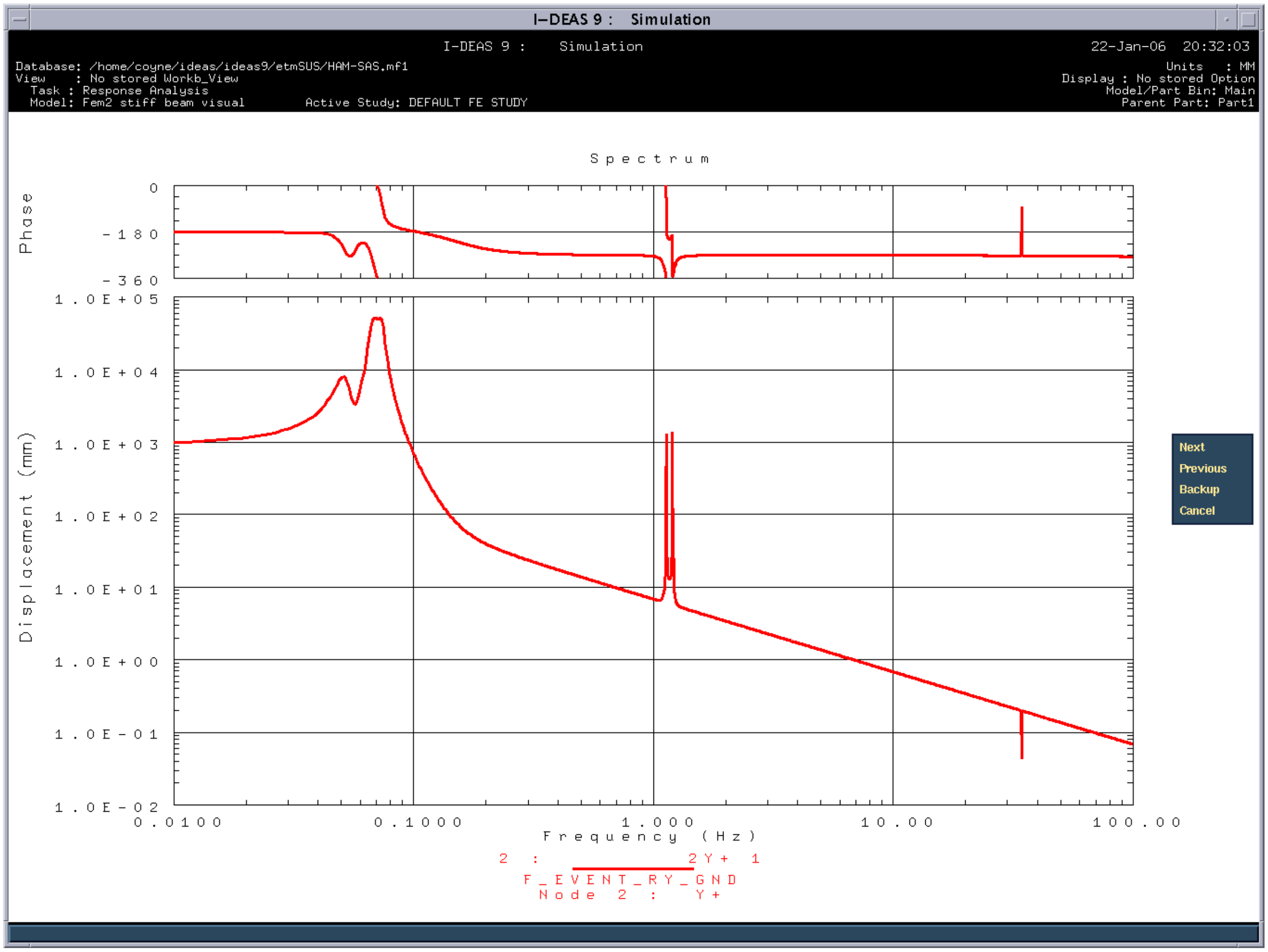
Figure 26: RY Ground Motion to Suspension Point Motion



```
                              I-DEAS 9 :     Simulation                          22-Jan-06   20:24:27
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                                     Units    : MM
View    : No stored Workb_View                                               Display : No stored Option
  Task : Response Analysis                                                        Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY               Parent Part: Part1
```



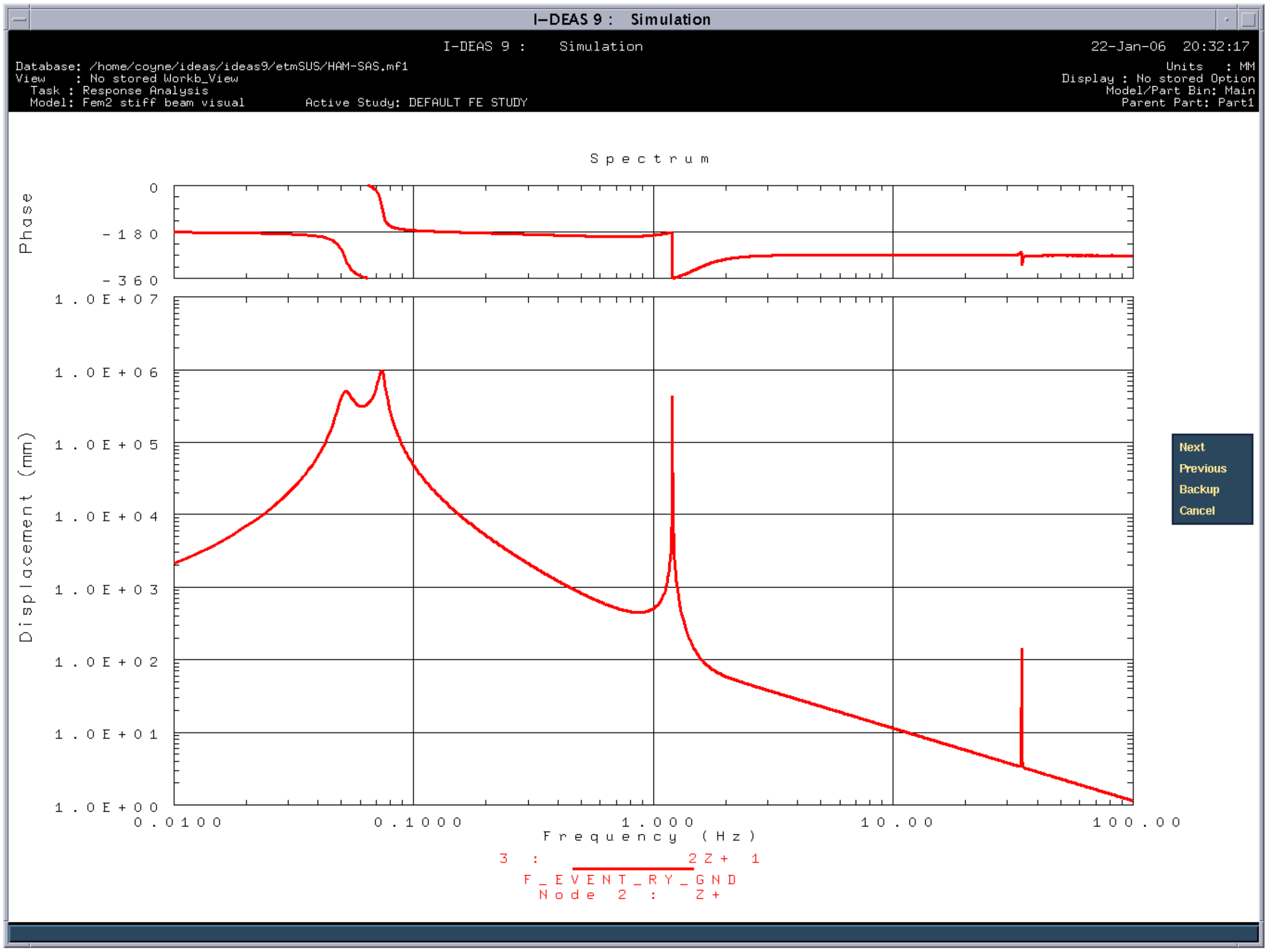
```
I-DEAS 9 :     Simulation                              22-Jan-06  20:31:46
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1              Units   : MM
View    : No stored Workb_View                     Display : No stored Option
  Task : Response Analysis                              Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY     Parent Part: Part1
```



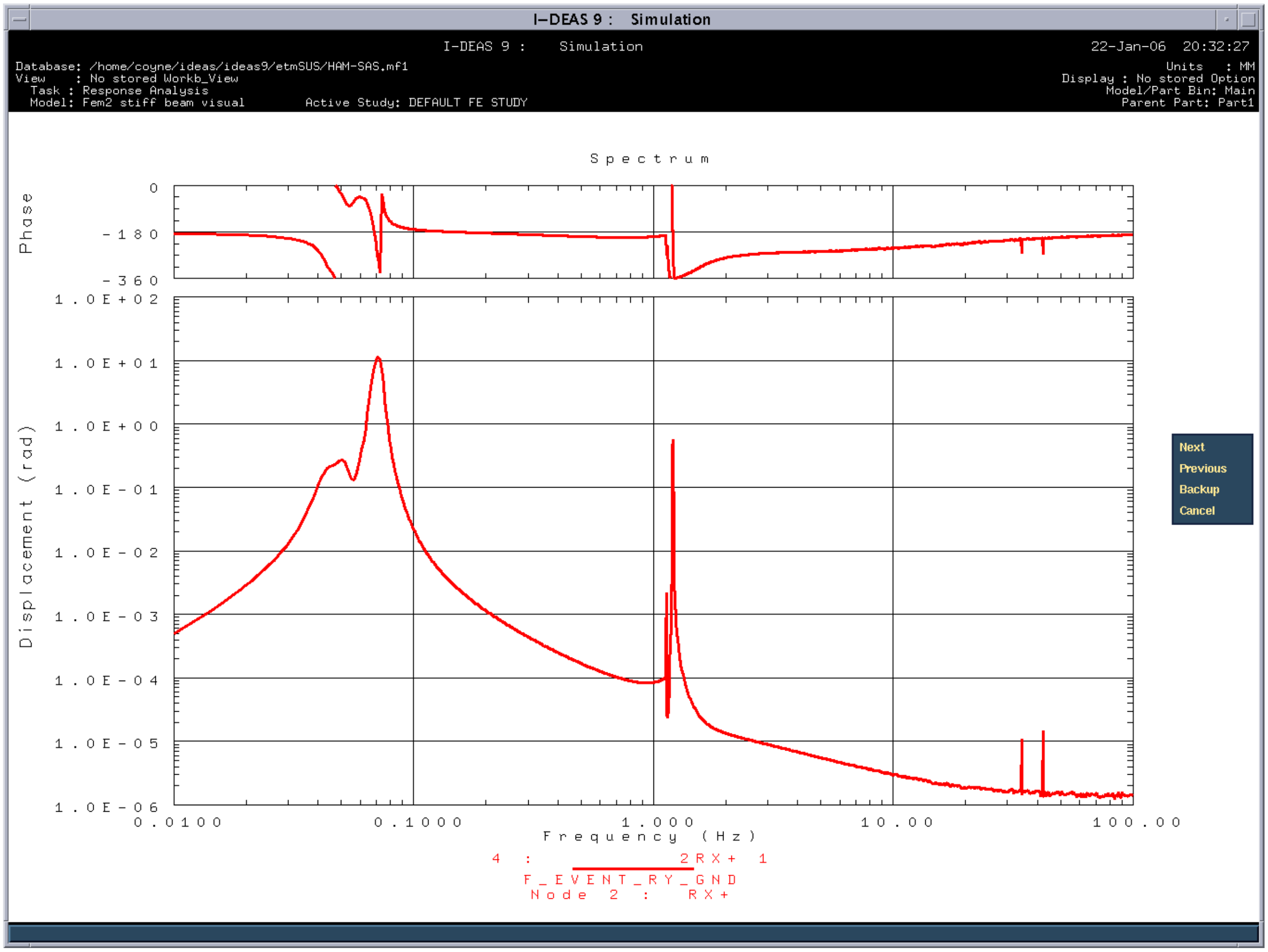
I-DEAS 9 : Simulation 22-Jan-06 20:32:03

Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1
View : No stored Workb_View
Task : Response Analysis
Model: Fem2 stiff beam visual Active Study: DEFAULT FE STUDY

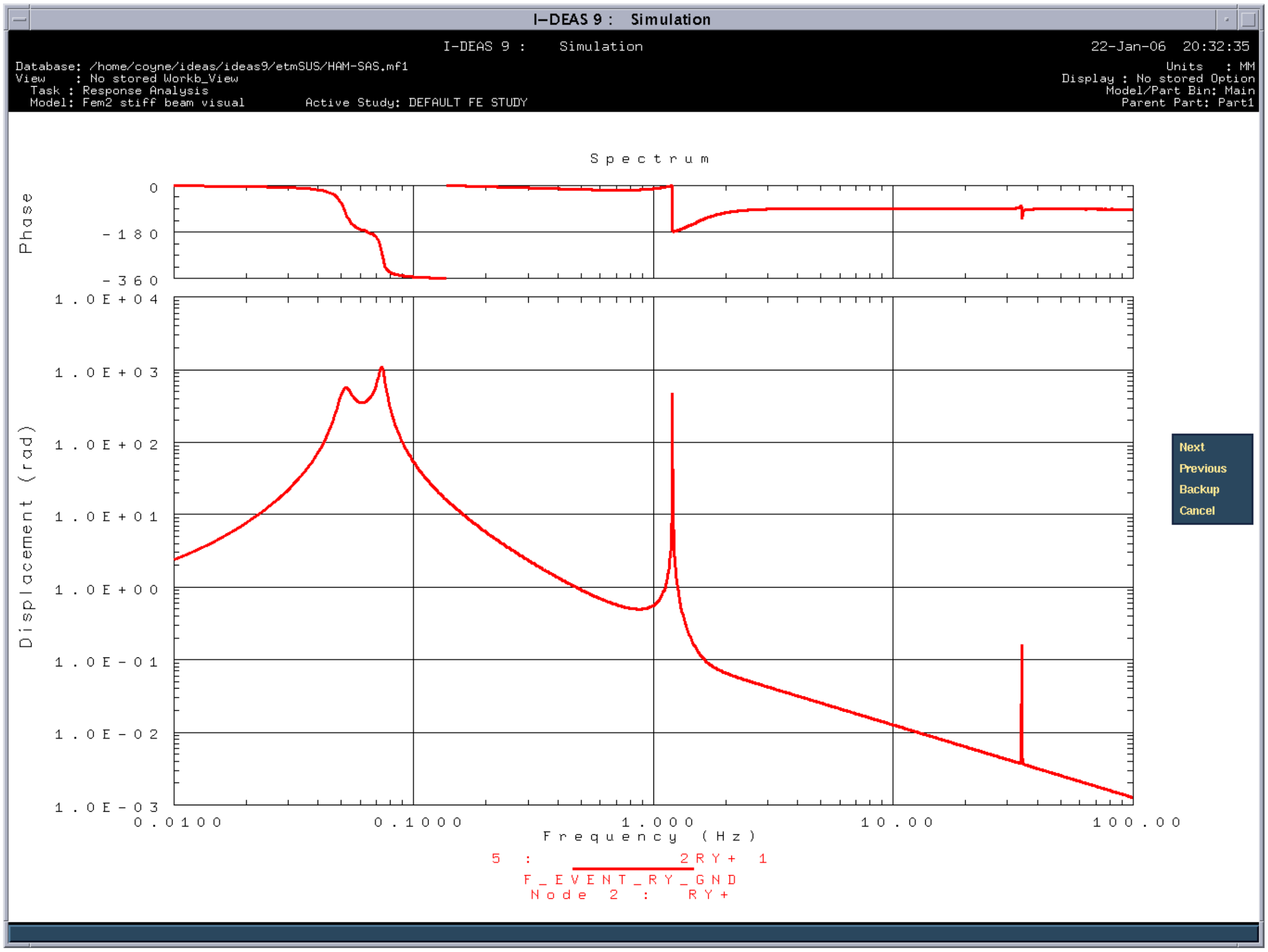
Units : MM
Display : No stored Option
Model/Part Bin: Main
Parent Part: Part1



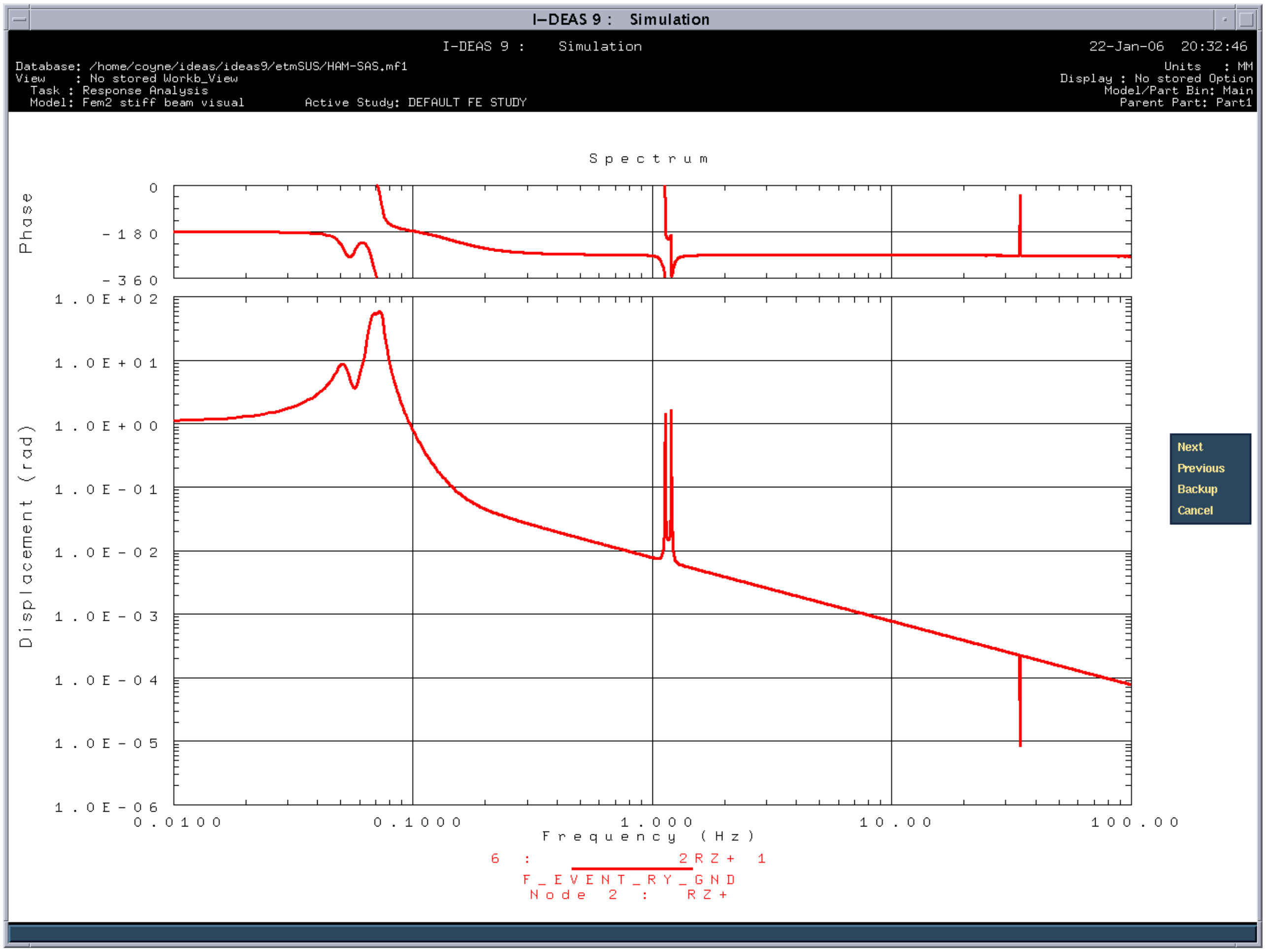
```
I-DEAS 9 :     Simulation                                   22-Jan-06   20:32:17
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                 Units    : MM
View    : No stored Workb_View                          Display : No stored Option
  Task : Response Analysis                                  Model/Part Bin: Main
  Model: Fem2 stiff beam visual       Active Study: DEFAULT FE STUDY   Parent Part: Part1
```



```
I-DEAS 9 :     Simulation                                    22-Jan-06   20:32:27
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                 Units   : MM
View    : No stored Workb_View                         Display : No stored Option
  Task : Response Analysis                                   Model/Part Bin: Main
  Model: Fem2 stiff beam visual       Active Study: DEFAULT FE STUDY    Parent Part: Part1
```

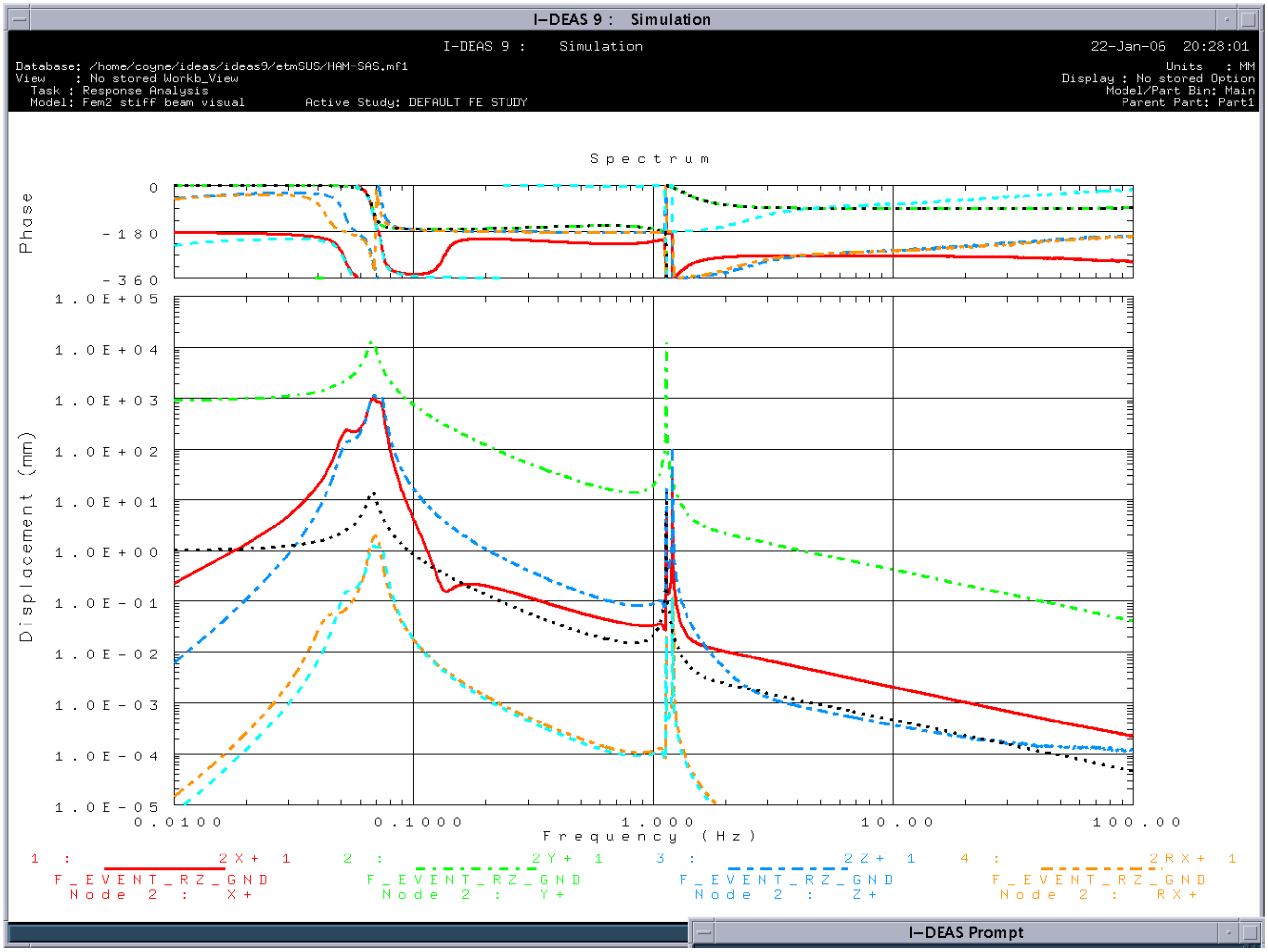


```
I-DEAS 9 :     Simulation                                           22-Jan-06   20:32:35
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                     Units    : MM
View     : No stored Workb_View                            Display : No stored Option
  Task : Response Analysis                                       Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY     Parent Part: Part1
```

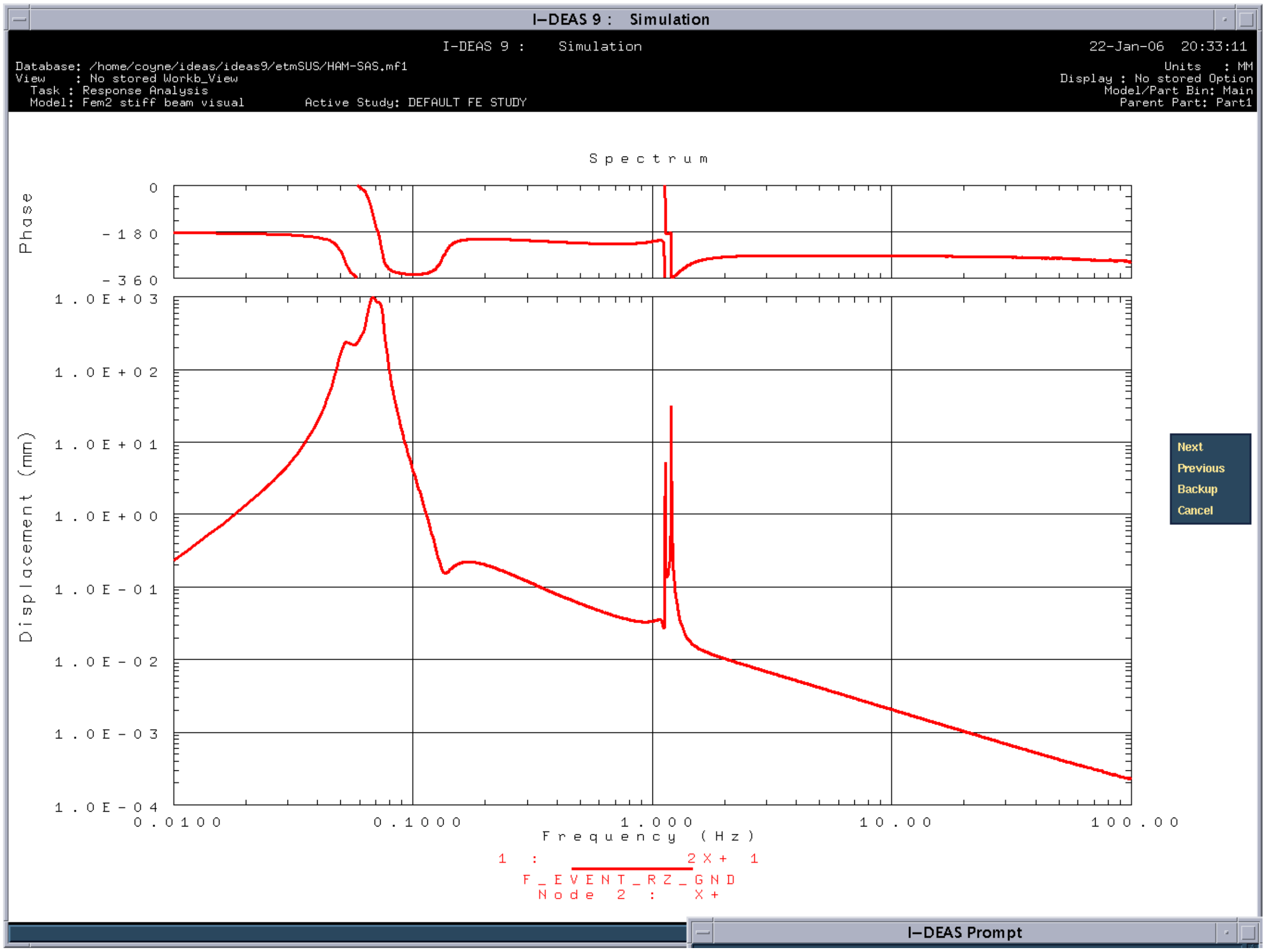


```
I-DEAS 9 :     Simulation                                        22-Jan-06  20:32:46
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                       Units   : MM
View    : No stored Workb_View                                  Display : No stored Option
  Task : Response Analysis                                           Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY       Parent Part: Part1
```

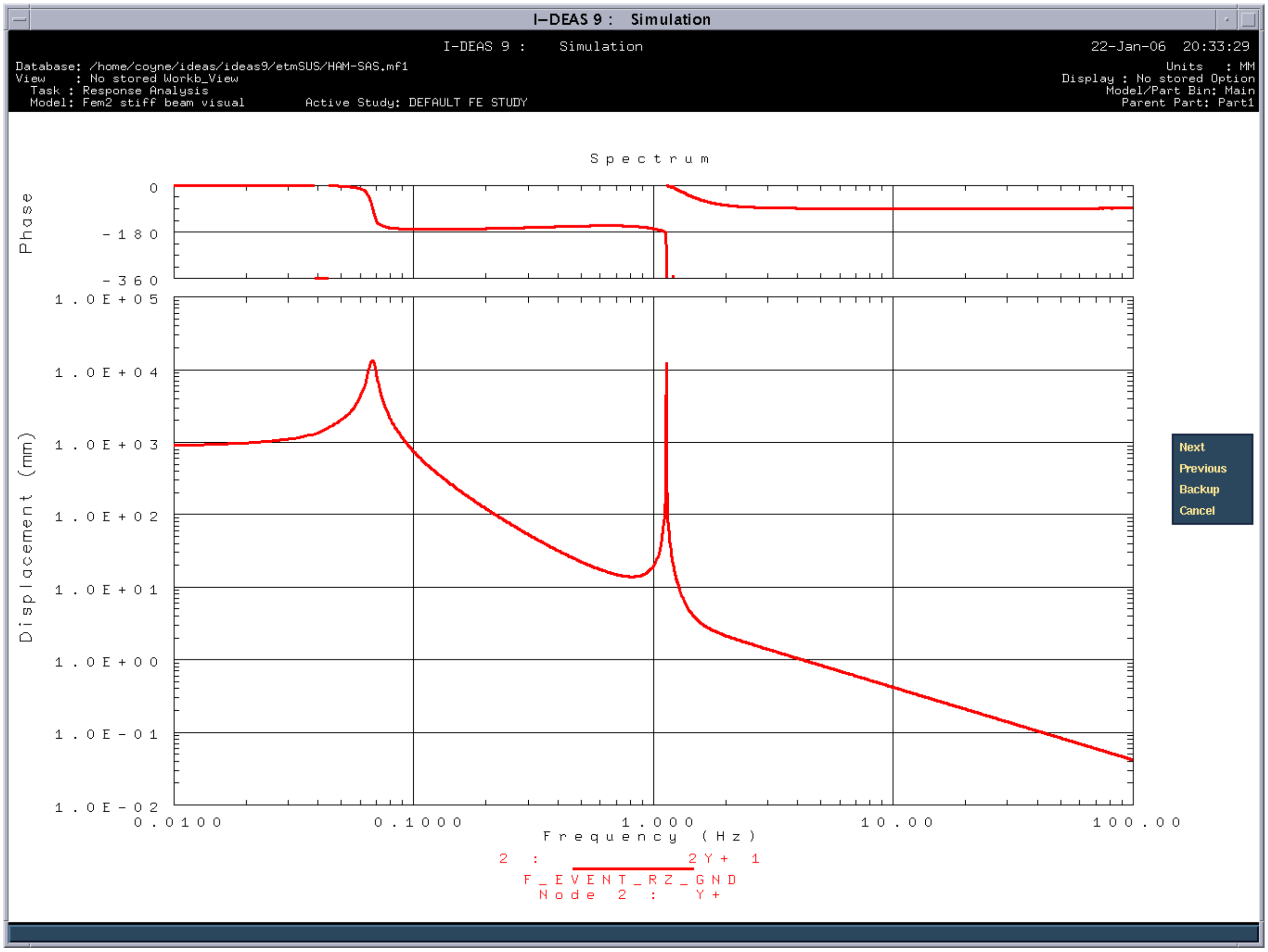
Figure 27: RZ Ground Motion to Suspension Point Motion



```
I-DEAS 9 :     Simulation                                22-Jan-06  20:28:01
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                Units   : MM
View    : No stored Workb_View                          Display : No stored Option
  Task : Response Analysis                                     Model/Part Bin: Main
  Model: Fem2 stiff beam visual      Active Study: DEFAULT FE STUDY  Parent Part: Part1
```



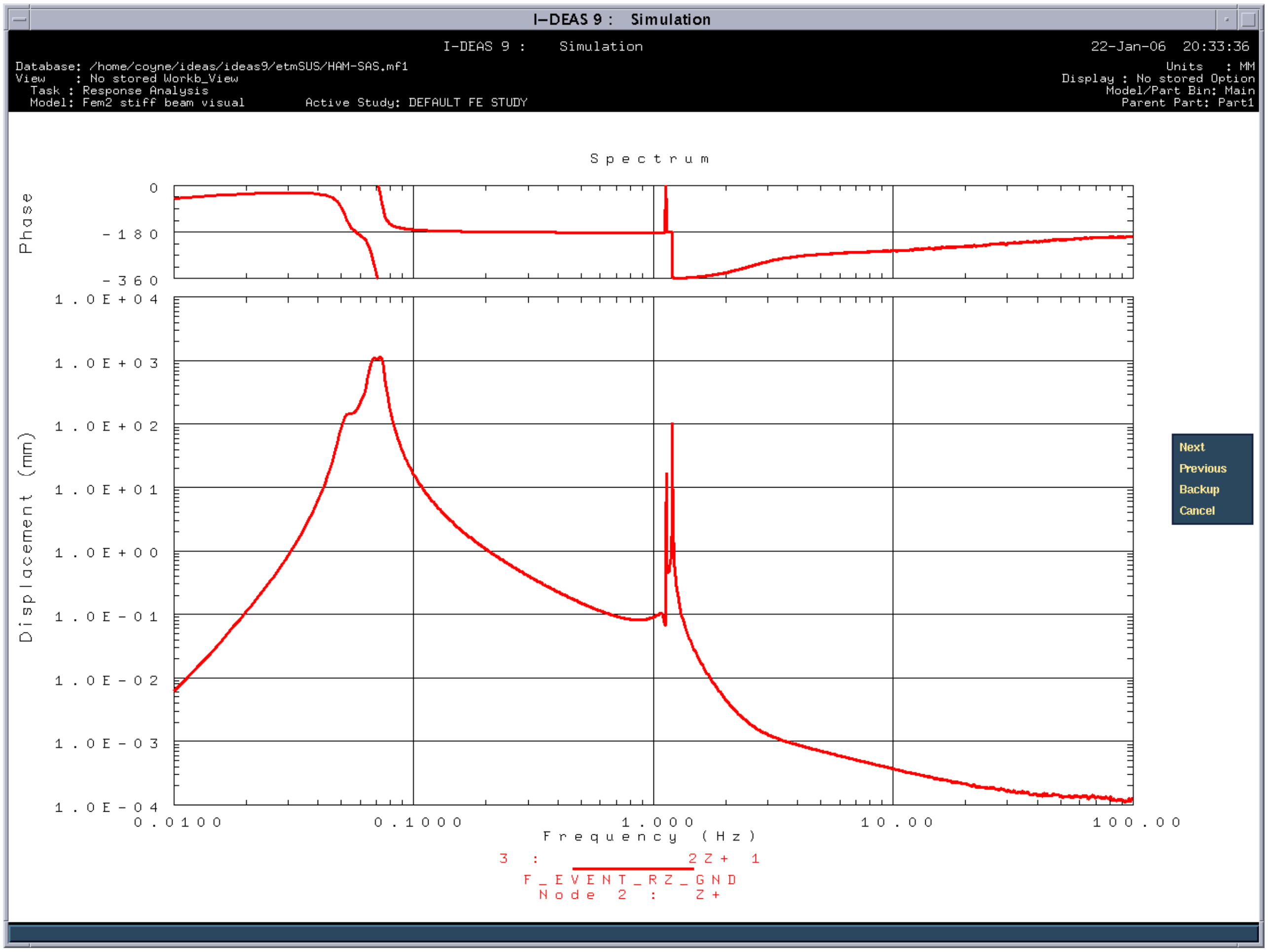
```
I-DEAS 9 :     Simulation                                22-Jan-06  20:33:11
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                 Units   : MM
View    : No stored Workb_View                          Display : No stored Option
  Task : Response Analysis                                     Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY     Parent Part: Part1
```



I-DEAS 9 : Simulation 22-Jan-06 20:33:29

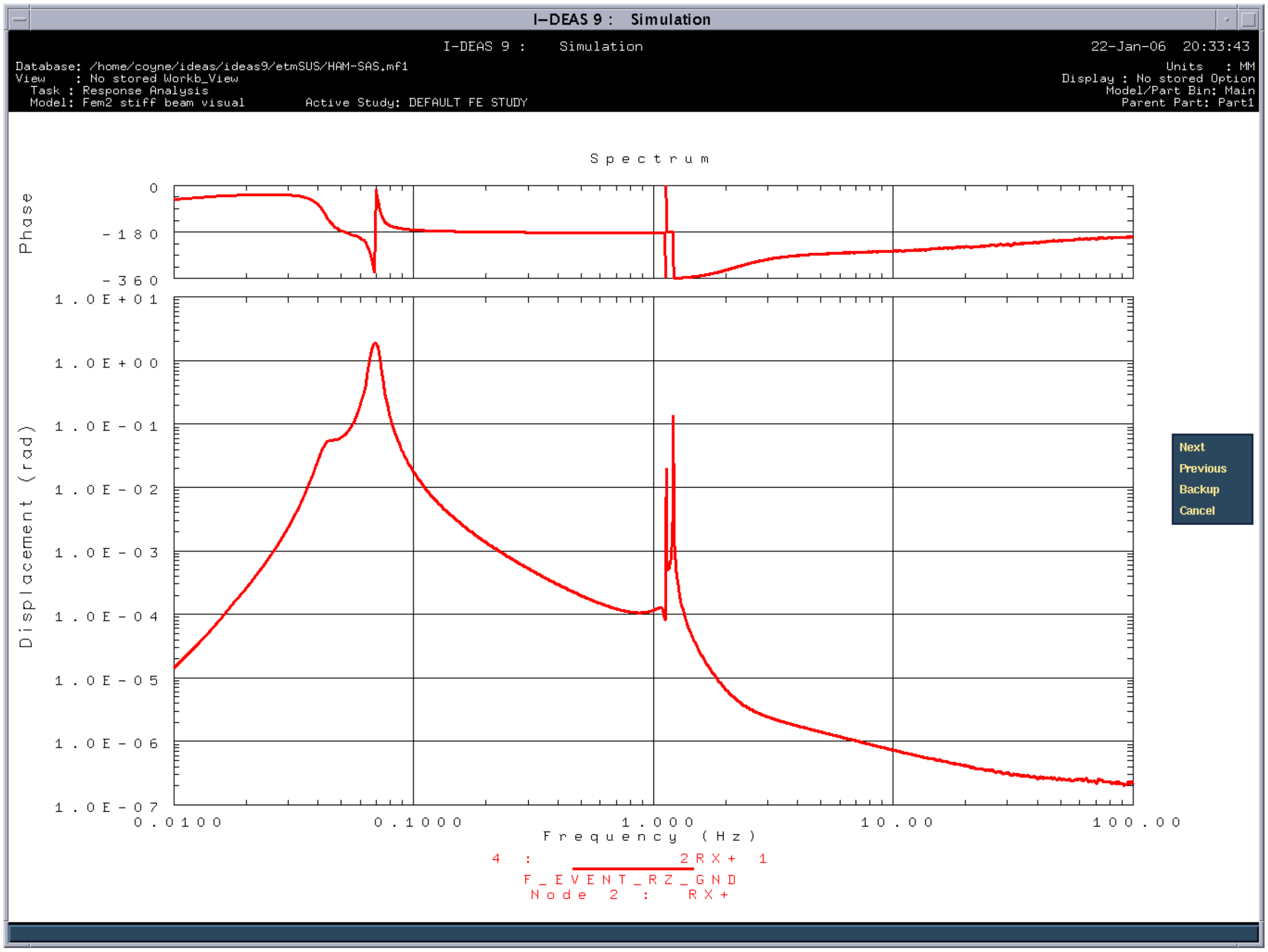
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1
View : No stored Workb_View
Task : Response Analysis
Model: Fem2 stiff beam visual Active Study: DEFAULT FE STUDY

Units : MM
Display : No stored Option
Model/Part Bin: Main
Parent Part: Part1

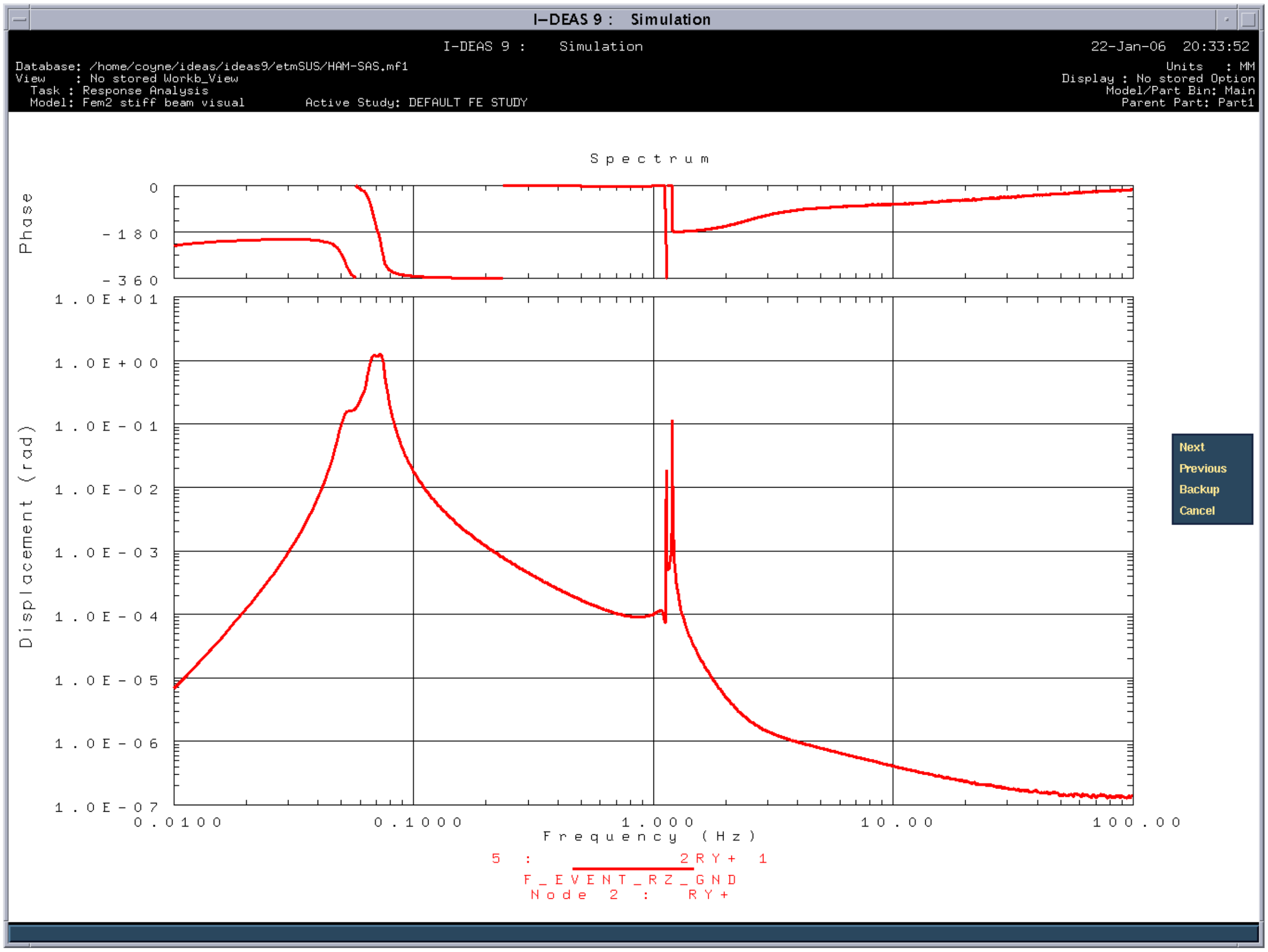


I–DEAS 9 : Simulation

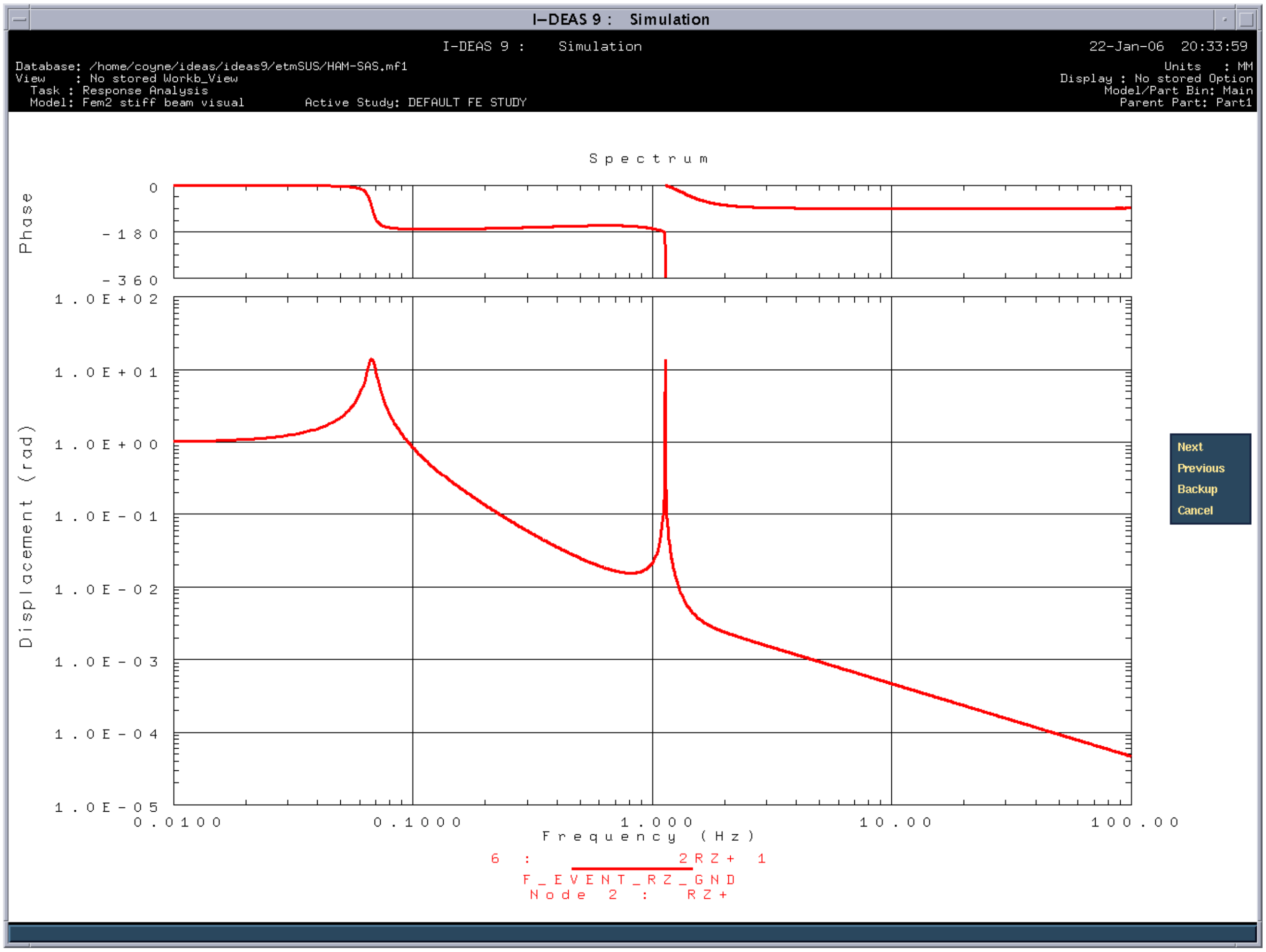
```
                              I-DEAS 9 :     Simulation                              22-Jan-06   20:33:36
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                                          Units    : MM
View     : No stored Workb_View                                                    Display : No stored Option
  Task : Response Analysis                                                             Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY                     Parent Part: Part1
```



```
I-DEAS 9 :   Simulation

I-DEAS 9 :    Simulation                                        22-Jan-06   20:33:43
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                     Units    : MM
View    : No stored Workb_View                                  Display : No stored Option
  Task : Response Analysis                                       Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY      Parent Part: Part1
```



```
I–DEAS 9 :  Simulation

                    I-DEAS 9 :    Simulation                          22-Jan-06   20:33:52
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                             Units    : MM
View    : No stored Workb_View                                       Display : No stored Option
  Task : Response Analysis                                             Model/Part Bin: Main
  Model: Fem2 stiff beam visual        Active Study: DEFAULT FE STUDY      Parent Part: Part1
```



```
I-DEAS 9 :     Simulation                                   22-Jan-06  20:33:59
Database: /home/coyne/ideas/ideas9/etmSUS/HAM-SAS.mf1                  Units    : MM
View     : No stored Workb_View                          Display : No stored Option
  Task : Response Analysis                                Model/Part Bin: Main
  Model: Fem2 stiff beam visual      Active Study: DEFAULT FE STUDY    Parent Part: Part1
```

4.3.2 Actuation to Sensing

TBD

4.4 State Space Model

TBD

5 Conclusions and Future Work

6 Appendix A: Key Geometry & Parameters

HAM-SAS Finite Element Key Data

Cardinal Points

#	Description	radius (mm)	theta (deg)	X (mm)	Y (mm)	Z (mm)	Comments
0	coordinate origin (optics table center, top surface)			0	0	0	
1	representative triple SUS suspension point (+x)			900	0	828	height from D020700 MC Triple Assy SolidWorks Model (top of upper blade to base of structure)
2	representative triple SUS suspension point (+y)			0	900	828	
3	representative location on optics table			707	707	0	1 meter offset from center on the optics table surface
4	optics table C.G.			0	0	-169	c.g. assumed at table center -- NOT CORRECT
5	connection table center (x-y plane, quadrant 1)			552.5	500	-353	use y-z plane node reflection to generate quadrants 2, then xz plane reflection to generate quadrants 3,4 central support & clamp pts. are defined at clamped edges of blades
6	connection nose tip (x-y plane, quadrant 1)			552.5	500	-435	
7	blade central support, position 1 (x-y plane, quadrant 1)	39	0	591.5	500	-465	
8	blade central support, position 2 (x-y plane, quadrant 1)		45	580.0772	527.5772	-465	
9	blade central support, position 3 (x-y plane, quadrant 1)		90	552.5	539	-465	
10	blade central support, position 4 (x-y plane, quadrant 1)		135	524.9228	527.5772	-465	
11	blade central support, position 5 (x-y plane, quadrant 1)		180	513.5	500	-465	
12	blade central support, position 6 (x-y plane, quadrant 1)		225	524.9228	472.4228	-465	
13	blade central support, position 7 (x-y plane, quadrant 1)		270	552.5	461	-465	
14	blade central support, position 8 (x-y plane, quadrant 1)		315	580.0772	472.4228	-465	
15	blade clamp, position 1 (x-y plane, quadrant 1)	289	0	841.5	500	-460	
16	blade clamp, position 2 (x-y plane, quadrant 1)		45	756.8539	704.3539	-460	
17	blade clamp, position 3 (x-y plane, quadrant 1)		90	552.5	789	-460	
18	blade clamp, position 4 (x-y plane, quadrant 1)		135	348.1461	704.3539	-460	
19	blade clamp, position 5 (x-y plane, quadrant 1)		180	263.5	500	-460	
20	blade clamp, position 6 (x-y plane, quadrant 1)		225	348.1461	295.6461	-460	
21	blade clamp, position 7 (x-y plane, quadrant 1)		270	552.5	211	-460	
22	blade clamp, position 8 (x-y plane, quadrant 1)		315	756.8539	295.6461	-460	
23	motorized spring top end (rigid connect. to optics table), quadrant 1			TBD	TBD	TBD	
24	motorized spring bottom end (rigid connect. to spring box), quadrant 1			TBD	TBD	TBD	
25	spring box C.G.			0	0	-468.5	c.g. at box x-y center by symmetry c.g. height assumed to be at vertical center -- INCORRECT, CHECK SW
26	small flex joint base plate (+x)			450	0	-417.5	use y-z plane nodal reflection to generate (-x) IP points are defined at ends of flexure beam radius V-accelerometer location is notional (side of optics table) Note: SolidWorks overall assy shows flex joint base at -906 mm
27	top leg disk (+x)			450	0	-392.5	
28	flex joint connector (+x)			450	0	-860.5	
29	flex joint base (+x)			450	0	-910.5	
30	IP slide spring support A (+x)			349	180	-596	
31	IP slide spring support B (+x)			349	-180	-596	
32	IP slide central spring support (+x)			349	0	-596	
33	LVDT (+x)			618	64	-629	
34	Actuator (+x)			618	0	-629	
35	V-accelerometer (+x) [on optics table side]			987.5	0	-169	
36	H-accelerometer (+x) [on spring box]			912.5	0	-481	
37	small flex joint base plate (+y)			0	505	-417.5	use x-z plane nodal reflection to generate (-y) IP
38	top leg disk (+y)			0	505	-392.5	
39	flex joint connector (+y)			0	505	-860.5	
40	flex joint base (+y)			0	505	-910.5	
41	IP slide spring support A (+y)			0	404	-596	
42	IP slide spring support B (+y)			0	404	-596	
43	IP slide central spring support (+y)			0	404	-596	
44	LVDT (+y)			-64	673	-629	
45	Actuator (+y)			0	673	-629	
46	V-accelerometer (+y) [on optics table side]			0	886	-169	
47	H-accelerometer (+y) [on spring box]			0	811	-481	

7 Appendix B: GAS Filter Blade ANSYS macro

Analysis of the mode shape and frequency for the pre-stressed, large-amplitude deflected (nonlinear) blade can be problematic in ANSYS because the SSTIF and PSTRES options only apply to the first load step, whereas two load steps allow a more robust solution and are required (due to the path dependent nature of the loading) is forces are imposed instead of displacements at the blade tip. The following ANSYS macro generally succeeds in finding a solution.

```
!************************************************************************
! sasb13.mac
!************************************************************************
! macro to analyse nonlinear deflection of a SAS blade
! seems eiganvalue analysis subsequent to multi-step static load analysis
! takes the 1st boundary condition set, so need to clamp blade root at the
! outset and leave tip free to move
!
! set tip RX to the intended mounting angle 33 deg (RX=-1.3614)
! use nominal Meff * g vertical load
! vary tip UY to minimize f1
! vary vertical force with dFz to vary the vertical tip position
!
! Solution performed in a single load step so that the subsequent modal
! analysis includes all prestress and deformed geometry
!
!Dennis Coyne 20-jan-2006
!
finish
/CLEAR,START
/COM,ANSYS MODEL OF A SINGLE SAS BLADE: NONLINEAR, STATIC DEFLECTION
/PREP7
/TITLE,SAS BLADE
PSTRES,ON
!************************************************************************
!*    GEOMETRIC PARAMETERS
!************************************************************************
! values of parameters
! SI units (m,N)
```

```
! coordinate system, naming/parameter conventions per G. Cella et. al.,
! "Monolithic Geometric Anti-Spring Blades", Nuc Instr. & Meth in Phys Res A,
! 540 (2005) 502-19.

! trapezoidal blade approximation to the reference blade of D050120-01
L=0.273
a=0.072   ! blade root width
b=0.010   ! blade tip width
h=0.00215 ! blade thickness
theta0=45*3.1416/180  ! slope at clamped root
thetaL=-theta0-33*3.1416/180    ! change in slope at tip end
!thetaL=-.87414
!*

!**************************************************************************
!*     LOAD PARAMETERS
!**************************************************************************
!  Effective weight loading on a single blade
M=906          ! total mass, kg
nb=8           ! number of blades for each of the 4 GAS filters
Meff=M/(4*nb)  ! effective mass per blade
g=-9.84        ! gravitational acceleration, m/s^2

!Fy=-275           ! horizontal tip load
dYtip=0.04768
dFz=82.05         ! vertical offload spring force
Fz=Meff*g+dFz  ! vertical load on the blade tip

!**************************************************************************
!*     MATERIAL PROPERTIES
!**************************************************************************
maryoung=1.76e11
marpoiss=0.3
mardens=7800

MP,EX,1,maryoung
MP,EY,1,maryoung
```

```
MP,EZ,1,maryoung
MP,PRXY,1,marpoiss
MP,DENS,1,mardens

!*************************************************************************
!*     GENERATE GEOMETRY
!*************************************************************************
K,1,0,0,0,
K,2,-a/2,0,0,
K,3,a/2,0,0,
K,4,0,L*cos(theta0),L*sin(theta0),
K,5,-b/2,L*cos(theta0),L*sin(theta0),
K,6,b/2,L*cos(theta0),L*sin(theta0),
LSTR, 1, 4 ! line 1
LSTR, 4, 6 ! line 2
LSTR, 6, 3 ! line 3
LSTR, 3, 1 ! line 4
LSTR, 4, 5 ! line 5
LSTR, 5, 2 ! line 6
LSTR, 2, 1 ! line 7
AL,1,2,3,4 ! area 1
AL,1,5,6,7 ! area 2
!*

!*
! Plot Areas
aplot

!*************************************************************************
!*     MESH GEOMETRY
!*************************************************************************
!ET,1,SHELL63,0,0,1,,0,0
!ET,1,SHELL43,,,2
!ET,1,SHELL181,1
!ET,1,SHELL93
ET,1,SHELL63
TYPE,1     ! shell elements
```

```
MAT,1      ! maraging steel
R,1,h      ! blade thickness
REAL,1
ESIZE,a/8,0
MSHAPE,1,2D
amesh,1,2

! Add discrete mass at blade tip for eigenvlaue analysis
ET,2,MASS21,0,0,0
R,2,Meff,Meff,Meff,0,0,0
REAL,2
KMESH,4

EPLOT
FINISH

!************************************************************************
!   Static Preload Analysis
!************************************************************************
/SOLU
ANTYPE,STATIC
NLGEOM,ON
PSTRES,ON
!SSTIF,ON
!  Load Step 1:
! Vertical Force at blade tip
! Rx and UY at tip
FK,4,FZ,Fz,

! Clamp at blade root
DL, 4, ,UX,0
DL, 4, ,UY,0
DL, 4, ,UZ,0
DL, 4, ,ROTX,0
DL, 4, ,ROTY,0
DL, 4, ,ROTZ,0
DL, 7, ,UX,0
```

```
DL, 7, ,UY,0
DL, 7, ,UZ,0
DL, 7, ,ROTX,0
DL, 7, ,ROTY,0
DL, 7, ,ROTZ,0

! Set UY at tip
DL, 2, ,UY,dYtip
DL, 5, ,UY,dYtip
DK, 4,UY,dYtip

! TEMPORARY TRIAL
! Set blade tip Rx
DL, 2, ,ROTX,thetaL
DL, 5, ,ROTX,thetaL
DK, 4,ROTX,thetaL


! Load step options
NSUBST,100,100,100
NEQIT,200
CNVTOL,U,,0.1
CNVTOL,ROT,,0.1
CNVTOL,F,,0.01
CNVTOL,M,,0.01
!OUTRES, ...
!OUTPR, ...
SOLVE

!  Load Step 2:
! Set blade tip Rx
!DL, 2, ,ROTX,thetaL
!DL, 5, ,ROTX,thetaL
!DK, 4,ROTX,thetaL

! Load step options
!NSUBST,100,100,100
```

```
!NEQIT,200
!CNVTOL,U,,0.1
!CNVTOL,ROT,,0.1
!CNVTOL,F,,0.01
!CNVTOL,M,,0.01
!OUTRES, ...
!OUTPR, ...
!SOLVE

EMATWRITE,YES
!EMATCREATE,YES
FINISH

! N.B.: The following /POST1 commands screw up the mode shape
! so only use to get tip position & frequencies and then re-run for mode shape
*CREATE,PTIP,MAC
/POST1
NSEL,S,LOC,X,0
NSEL,R,LOC,Y,L*cos(theta0)
!PRNSOL,U,X
!PRNSOL,U,Y
PRNSOL,U,Z
!PRNSOL,ROT,X
!PRNSOL,ROT,Y
!PRNSOL,ROT,Z
FINISH
*END
PTIP

!**************************************************************************
!   Eigenvalue Analysis
!**************************************************************************
*CREATE,MODES,MAC
/SOL
ANTYPE,MODAL
UPCOORD,1.0,ON
PSTRES,ON
```

```
!SSTIF,ON
!LUMPM,OFF

nmodes=2
MODOPT,LANB,nmodes
MXPAND,
PSOLVE,EIGLANB
FINISH
/SOLU   ! Additional solution step for modal expansion
EXPASS,ON
PSOLVE,EIGEXP  ! Expand the eigenvector solution. Required to view mode shapes
FINISH
*END

! Use ! to comment out "MODES" if only a static solution is wanted
MODES
```