



NSTX Upgrade

Modal Analysis and Normal Operation Transient Load Effects

NSTXU-CALC-133-13-00

Rev 0

June 2011

Prepared By:

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Phil Heitzenroeder, Head, Mechanical Engineering
For NSTX Cognizant Engineer (P H. Titus)

PPPL Calculation Form

Calculation # **NSTXU-CALC-133-13-00** Revision # 00 WP #. 0029,0037
(ENG-032)

Purpose of Calculation: (Define why the calculation is being performed.)

The purpose of this calculation is to address a concern that normal operational transient current profiles might introduce structural dynamic effects that could increase the static loading in evaluations that are being used for the coils and global structure. This is for normal operation - not disruptions. Disruptions have strong dynamic effects and these are addressed in evaluations of disruption loads on the passive plates [10], and other vessel internals as well as the global vessel response.

References (List any source of design information including computer program titles and revision levels.)

-See the reference list in the body of the calculation

Assumptions (Identify all assumptions made as part of this calculation.)

Calculation (Calculation is either documented here or attached)

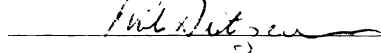
Attached in the body of the calculation

Conclusion (Specify whether or not the purpose of the calculation was accomplished.)

Normal operational transients occur slow enough that static analyses are appropriate

Cognizant Engineer's printed name, signature, and date

Phil Heitzenroeder for Peter H. Titus



I have reviewed this calculation and, to my professional satisfaction, it is properly performed and correct.

Checker's printed name, signature, and date

Fred Dahlgren131



13 Oct. 2011

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Modal Analysis and Normal Operation Transient Load Effects

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3.0 Executive Summary

Current profiles used in the NSTX machine involve some sharp transient changes in magnitude. This raised a concern that the load changes might produce some structural overshoot and subsequent oscillation of the response of the structures. NSTX current profiles are shown in Figure 4.0-1. This calculation addresses this concern that structural dynamic effects might increase the static loading in evaluations that are being used for NSTX coils and global structure. For all tokamaks that the author is familiar with, this has not been a concern or an observed phenomenon. But rigorously this needs to be shown, as a large body of NSTX normal operating load analyses assume static loading.

The concern is for normal operation - not disruptions. Disruptions have strong dynamic effects and these are addressed in evaluations of disruption loads on the passive plates, and other vessel internals [10] as well as the global vessel response. The global model of NSTX Center Stack Upgrade (NSTX-CSU) provides a simulation of the overall behavior of the machine. It provides boundary conditions for local models and sub models, or allows inclusion of the detailed models of components in the global model. The global model is used to compare with other models, and is also used as the model for computing influence coefficients for various parts of the machine. For this calculation, a segment of the global model was extracted and was loaded with transient loads to quantify the dynamic load factor. The outer TF leg was chosen for this study because the compliance of the outer leg was expected to be effected by the relatively slow variation of the normal scenario loads.

The design point currents and loads are published on the web and are maintained by C. Neumeyer. Published loads from normal operating current sets do not include any dynamic effects. Normal scenario

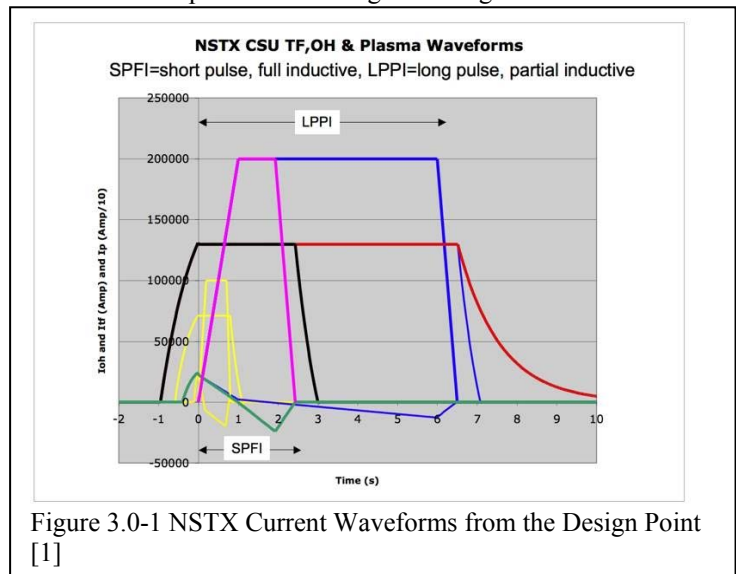


Figure 3.0-1 NSTX Current Waveforms from the Design Point [1]

loads are in general much less severe than loads that are based on worst case power supply currents. The project has implemented a digital coil protection system (DCPS) to preclude loads beyond the normal scenario loads. The conservatism of qualifying the max power supply loads, that might have enveloped the dynamic loading, has been removed.

Transient dynamic analysis of the outer TF leg is presented (section 9) and the "ringing" of the leg, after a sharp change in current magnitude, has been quantified. The oscillations that resulted from the sharp current change are less than 1% or .4% for out-of-plane loads, and .8% for in-plane loads. These are small alternating stresses, but they are superimposed on a substantial static stress that would be evaluated as a mean stress. The Goodman equation presented in the NSTX criteria document is used to calculate an equivalent $R=-1$ alternating stress which is then evaluated using NIST copper SN data. The results show a trivial fatigue damage from these oscillations. A transient analysis of the outer PF supports (section 10) also shows very small oscillations, and fatigue effects from dynamically applied normal operating loads on these components may also be neglected.

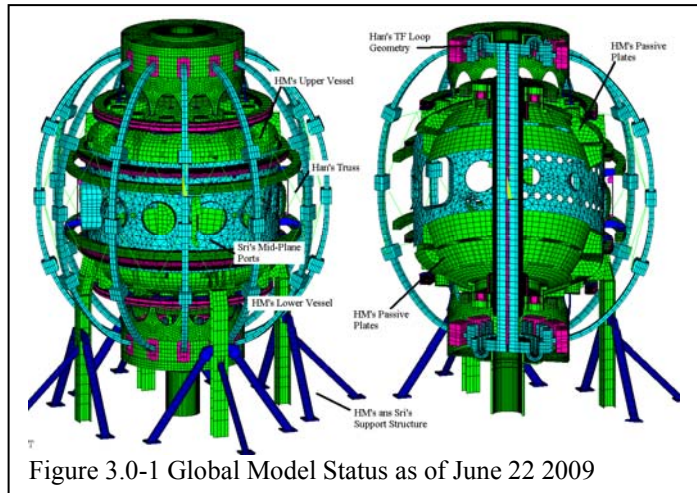


Figure 3.0-1 Global Model Status as of June 22 2009

4.0 Input to the Digital Coil Protection System

While a sharp transient could be evaluated in the DCPS, no input to the DCPS is planned based on this analysis. The nominal dynamic effects are small and are not required to be mitigated by the DCPS.

5.0 Design Input

5.4 References

- [1] NSTX Design Point Sep 8 2009 http://www.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html
- [2] NSTXU-CALC-13-001-00 Rev 1 Global Model – Model Description, Mesh Generation, Results, Peter H. Titus June 2011
- [3] NSTX Upgrade Seismic Analysis NSTXU-CALC-10-02-00 Rev 0 February 9 2011 Prepared By: Peter Titus
- [4] Analysis of Existing & Upgrade PF4/5 Coils & Supports – With Alternating Columns, NSTXU-CALC-12-05-00, Prepared By: Peter Titus, Reviewed by Irv Zatz, Cognizant Engineer: Mark Smith WBS 1.1.2
- [5] "Analysis of TF Outer Leg" Han Zhang NSTX Calculation Number 132-04-00
- [6] NSTX Structural Design Criteria Document, I. Zatz
- [7] ANSYS Structural Analysis Program, Revisions 10.0 through 13, Swanson Analysis Systems
- [8] National Spherical Torus Experiment NSTX CENTER STACK UPGRADE GENERAL REQUIREMENTS DOCUMENT NSTX_CSU-RQMTS-GRD Revision 0 March 30, 2009 Prepared By: Charles Neumeyer NSTX Project Engineering Manager
- [9] Vessel Rework for the Neutral Beam and Thomson Scattering Port NSTXU-CALC-24-01-00 Prepared By: T. Willard WBS 1.1.2 Reviewed by: A. Zolfaghari Cognizant Engineers: M. Smith, G. Labik, C. Priniski
- [10] NSTX Upgrade DISRUPTION ANALYSIS OF PASSIVE PLATES, VACUUM VESSEL AND COMPONENTS NSTXU-CALC-12-01-01 Rev 1 April, 2011, Prepared by Peter Titus
- [11] Damping in ANSYS/LS-Dyna Prepared by: Steven Hale, M.S.M.E Senior Engineering Manager CAE Associates (Web Search Results)

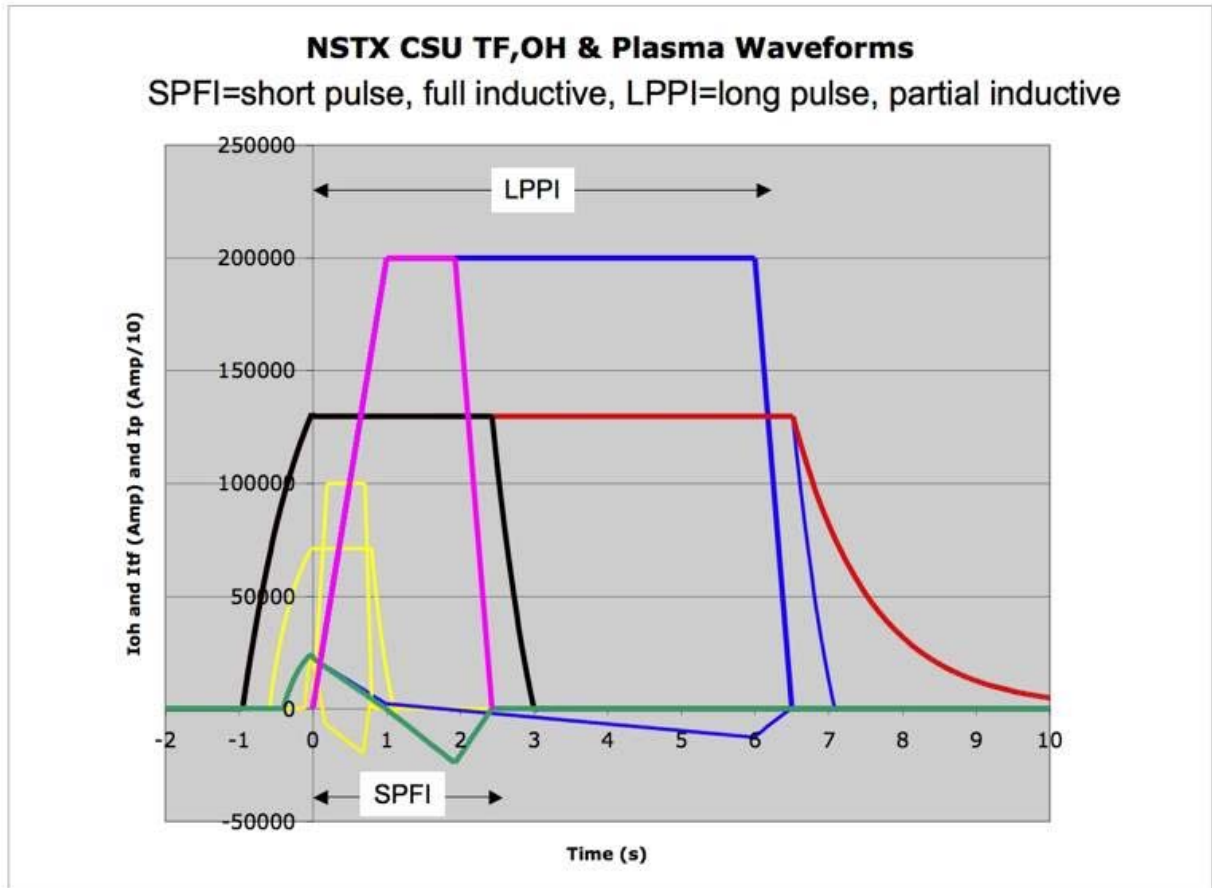


Figure 6.0-1 NSTX Current Waveforms from the Design Point Spreadsheet

6.0 Analysis Models

The analyses use separate model "pieces" which are brought into ANSYS as text listings similar to a CDWRITE or *.anf ANSYS file, using the /INPUT command. These segments are created in a separate program. The magnet components are meshed and the loading is computed from a model with only the magnets. Each piece is brought into ANSYS with a NUMOFF command. The last group of elements entered into the ANSYS program is the magnet model. Lorentz forces are computed in the same program used to mesh the structural components. This program is described in reference [2] section 6.2. Load files are also read into ANSYS in the solution phase. This approach allows computation of loading and re-use of the load files - as long as the magnet model does not change. Structural model "pieces" may be modified and the problem re-run without alteration of the load files. This is a practical way to limit run times for the multiple current sets required by the NSTX GRD.

6.1 Global Model reference [2]

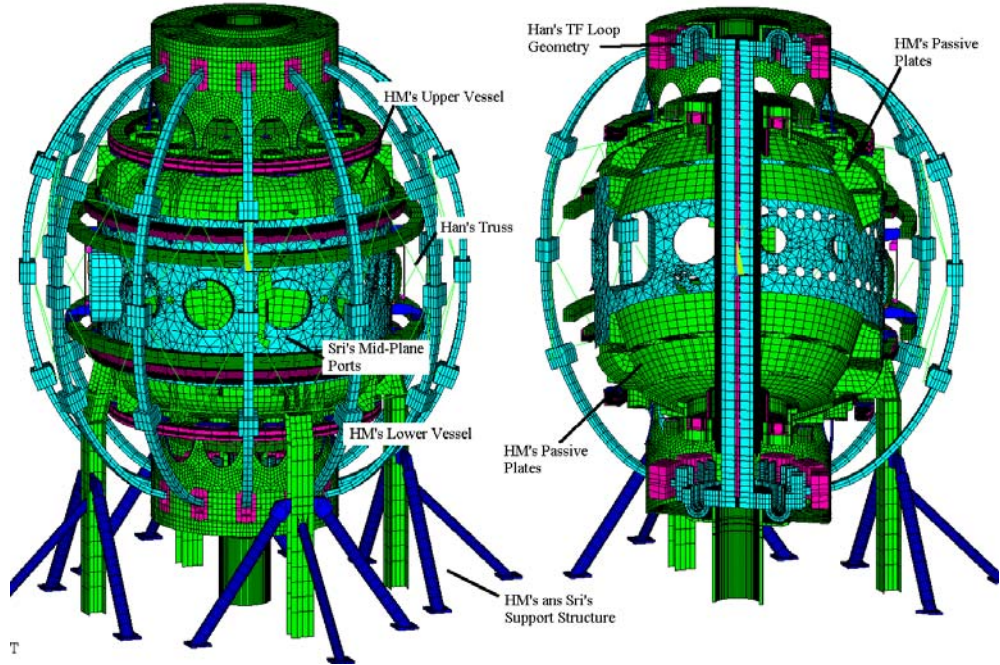


Figure 6.1-1 Global Model Status as of June 22 2009

6.2 Single TF Model

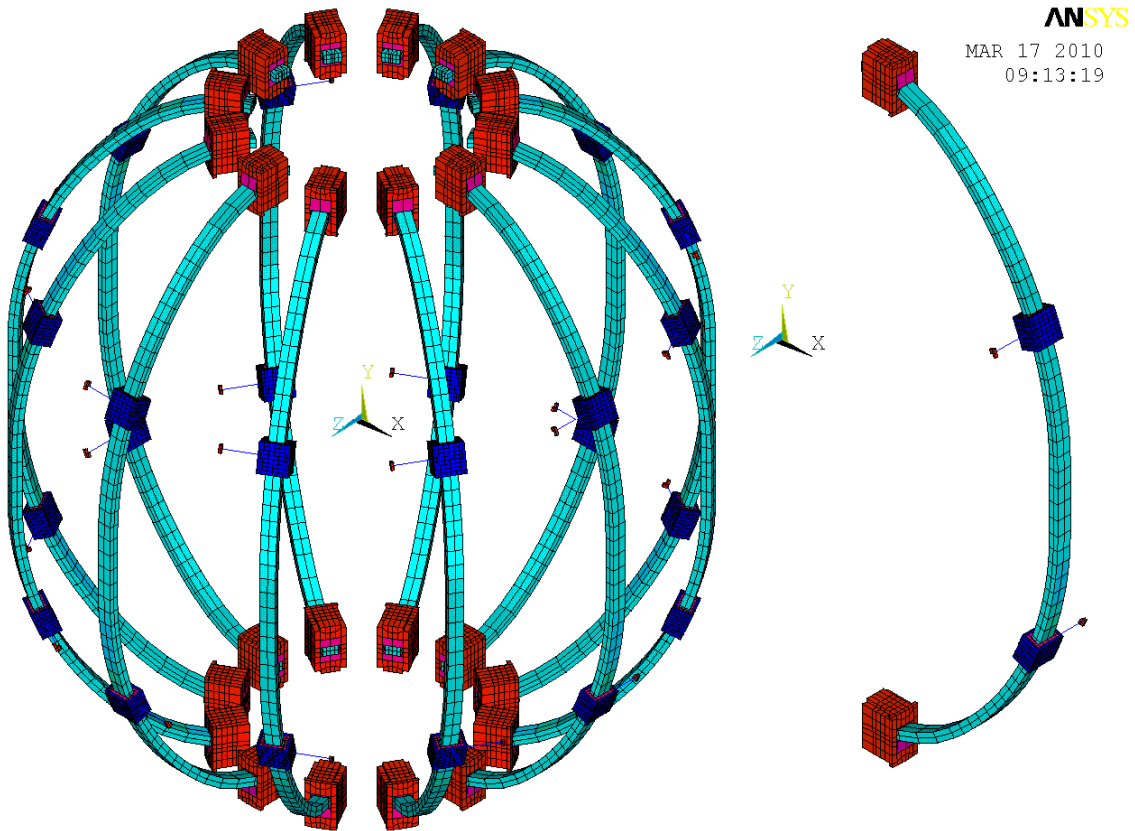
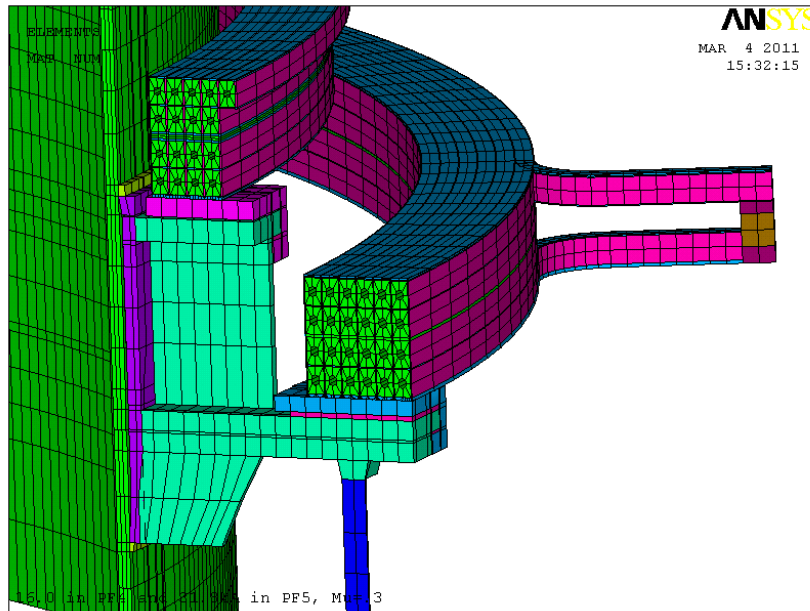


Figure 6.2-1 Single TF Analysis Model as of March 17 2010. A symmetry expansion of the 12 coil system is shown at left.

6.3 PF 4 and 5 Coil, Support and Vessel Model



7.0 Response of a Single Degree of Freedom Oscillator to Impulsive loads

From, Figure 6.0-1, NSTX Current Waveforms from the Design Point Spreadsheet, the ramp time is typically about one second. If that is considered 1/4 of a wave form the period would be 4 seconds and the frequency is .25 cycles per second. There are obviously some sharp changes in current magnitude that would introduce some effective higher frequency content. In section 8, a mode extraction analysis of the global model is presented.

Figure 7.0-1 is a scan of responses by a range of single degree of freedom oscillators to partial periods of forcing functions. This plot was created by integrating the spring mass equation of motion with no damping, for segments of a forcing function wave.

8.0 Modal Analysis

The modal analysis results included in this section are from an early global model dated Feb 2010. Reference [2] also includes some mode results from the seismic analysis of NSTX. In the seismic analysis, the first mode is 7.552 cps. Throughout the NSTX design process the global model grew but the fundamental frequencies remained similar. The tokamak fundamental frequencies start at around 7.5 to 8 cps. The forcing function is approximately .25 cps and the ratio of forcing function to natural frequency is $.25/8 = .031$ which puts the

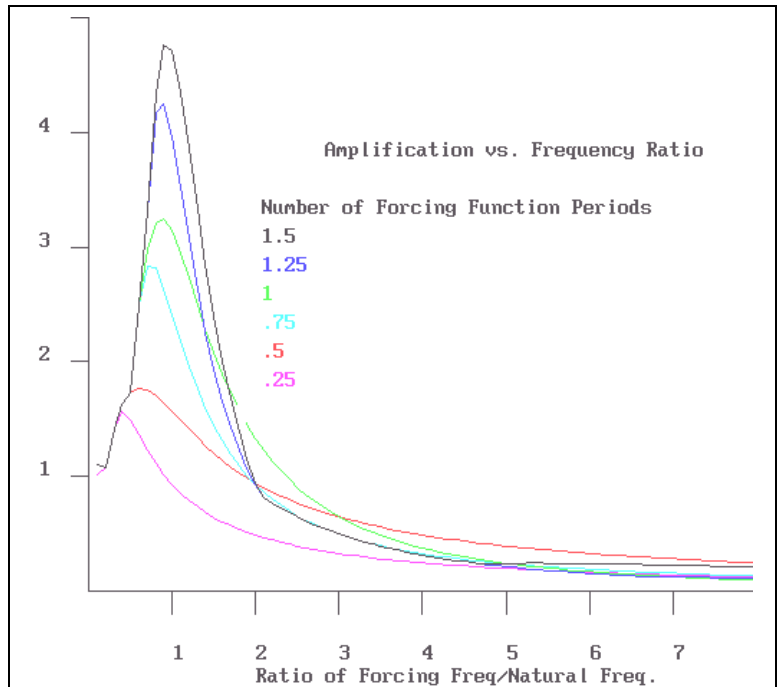


Figure 7.0-1 Amplification factor, or DLF – Single degree of freedom oscillator with a “truncated” harmonic forcing function. Half a wavelength, or a load pulse of half a period would give a peak DLF of ~1.7 - if the frequency ratio is uncertain. For a high frequency pulsed load acting on a low frequency structure, the dynamic amplification factor is less than one.

amplification factor close to 1.0. This is the simple argument that is typically employed to justify static analysis for normal scenario loads. The sharp changes at the end of the ramp up and the beginning of ramp down might introduce some DLF associated with the instantaneously changing currents. These will be addressed by dynamic simulations of the TF loads and PF 4 and 5 Loads in Sections 9 and 10.

```

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  2        8.453498965131
  3        8.584025859676
  4        21.53271441733
  5        21.70848351210
  6        27.55140453170
  7        27.68320781447
  8        31.24146496544
  9        39.47346890219
 10        39.48732031026
 11        41.38617076385
 12        42.78152229142
 13        43.75369490750
 14        44.58972940610
 15        45.34181735651
 16        45.65344434115
 17        45.76558638657
 18        45.99066637408
 19        46.11637681959
 20        46.13189791745
 21        46.40076537421
 22        46.52080939177
 23        46.61707554874
 24        46.92496135445
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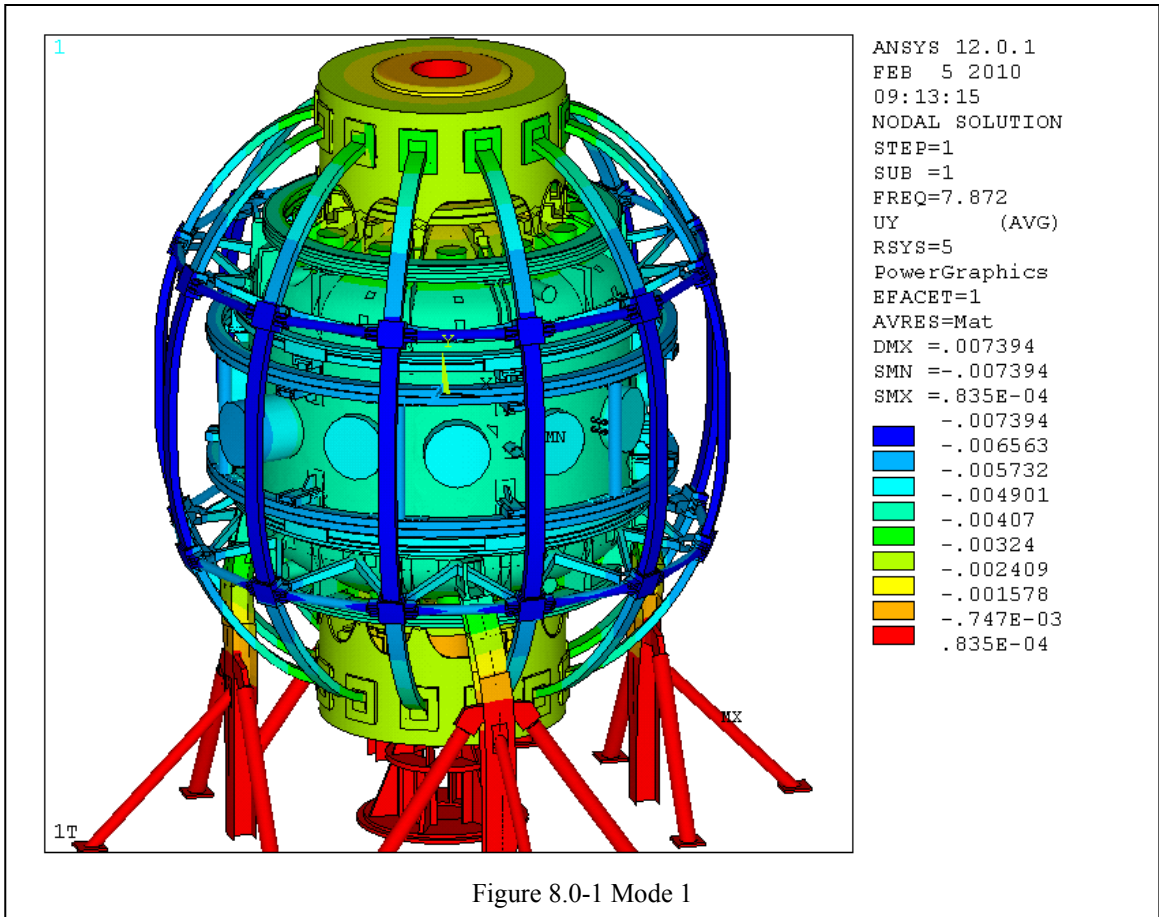
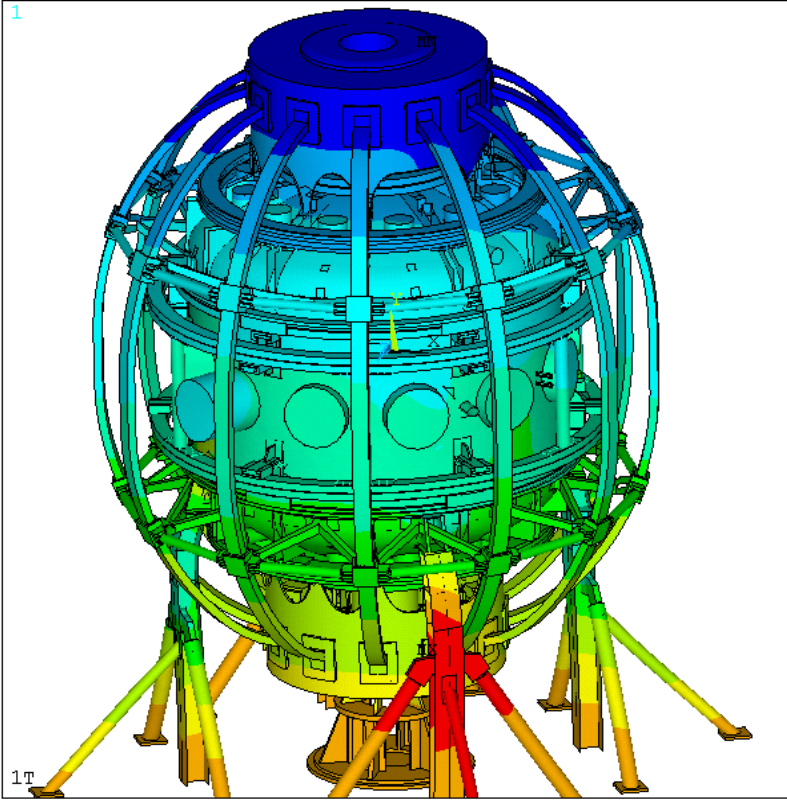


Figure 8.0-1 Mode 1

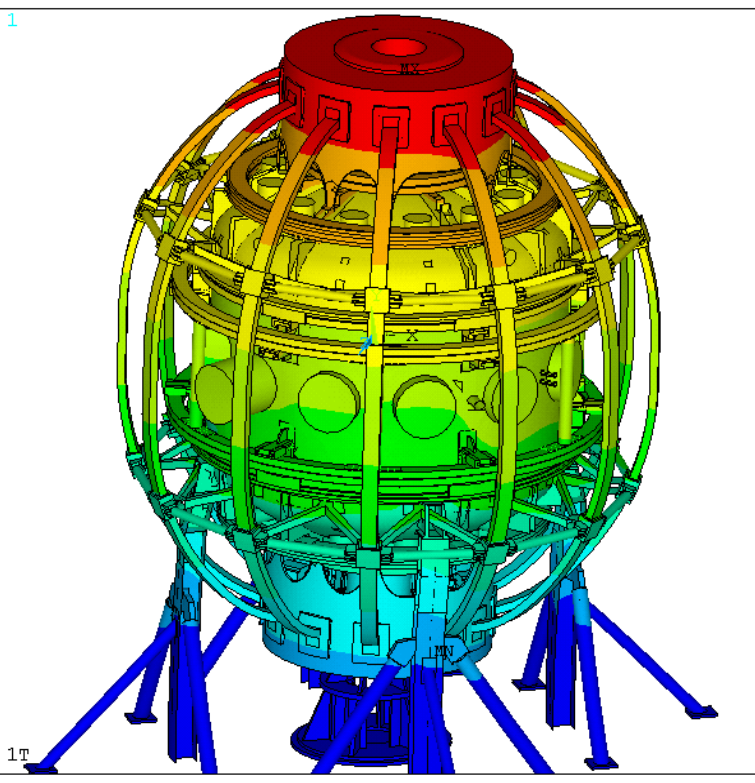
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RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.006172
SMN =-.002122
SMX =.455E-03
-.002122
-.001836
-.001549
-.001263
-.976E-03
-.690E-03
-.404E-03
-.117E-03
.169E-03
.455E-03
```

Figure 8.0-2 Mode 2

1



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FEB 5 2010
09:17:17
NODAL SOLUTION
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FREQ=8.584
UX      (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.006151
SMN =-.304E-05
SMX =.005781
-.304E-05
.640E-03
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.001925
.002568
.00321
.003853
.004495
.005138
.005781
```

Figure 8.0-3 Mode 3

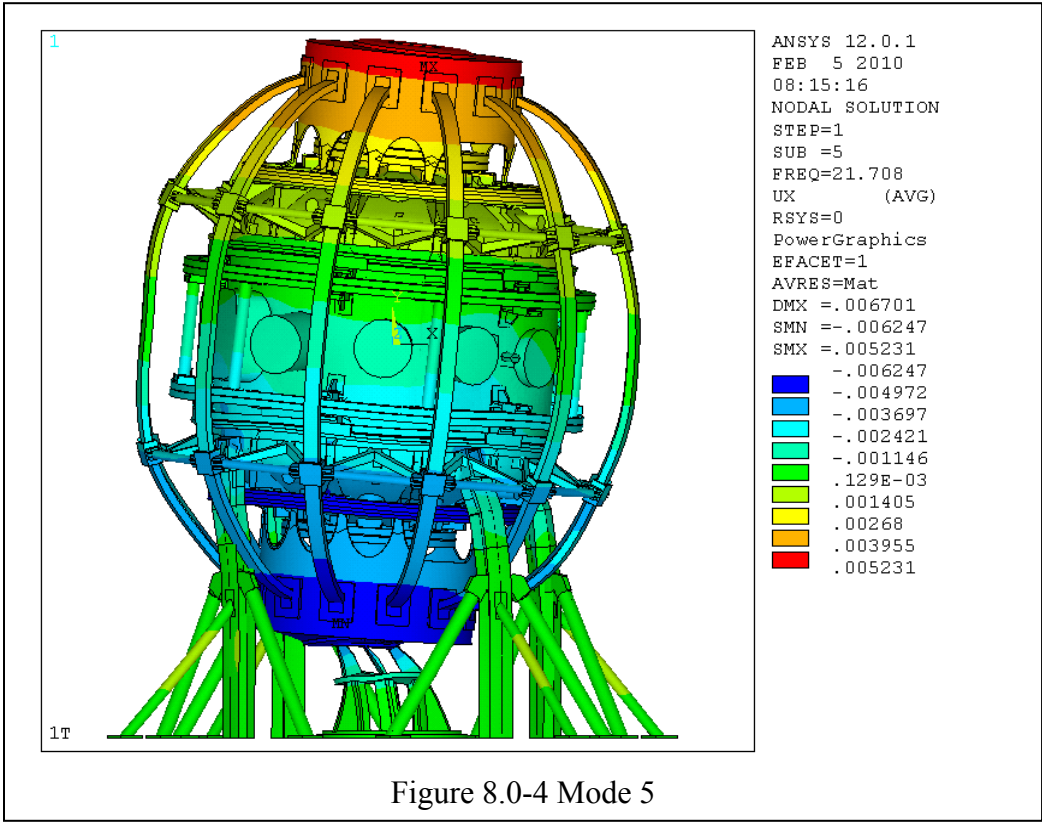


Figure 8.0-4 Mode 5

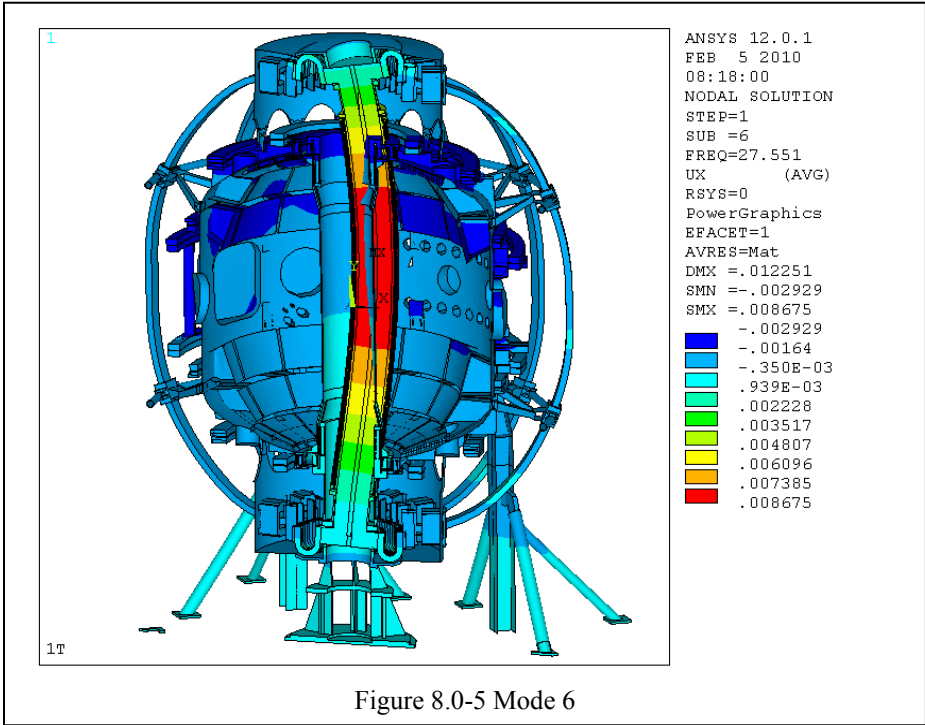
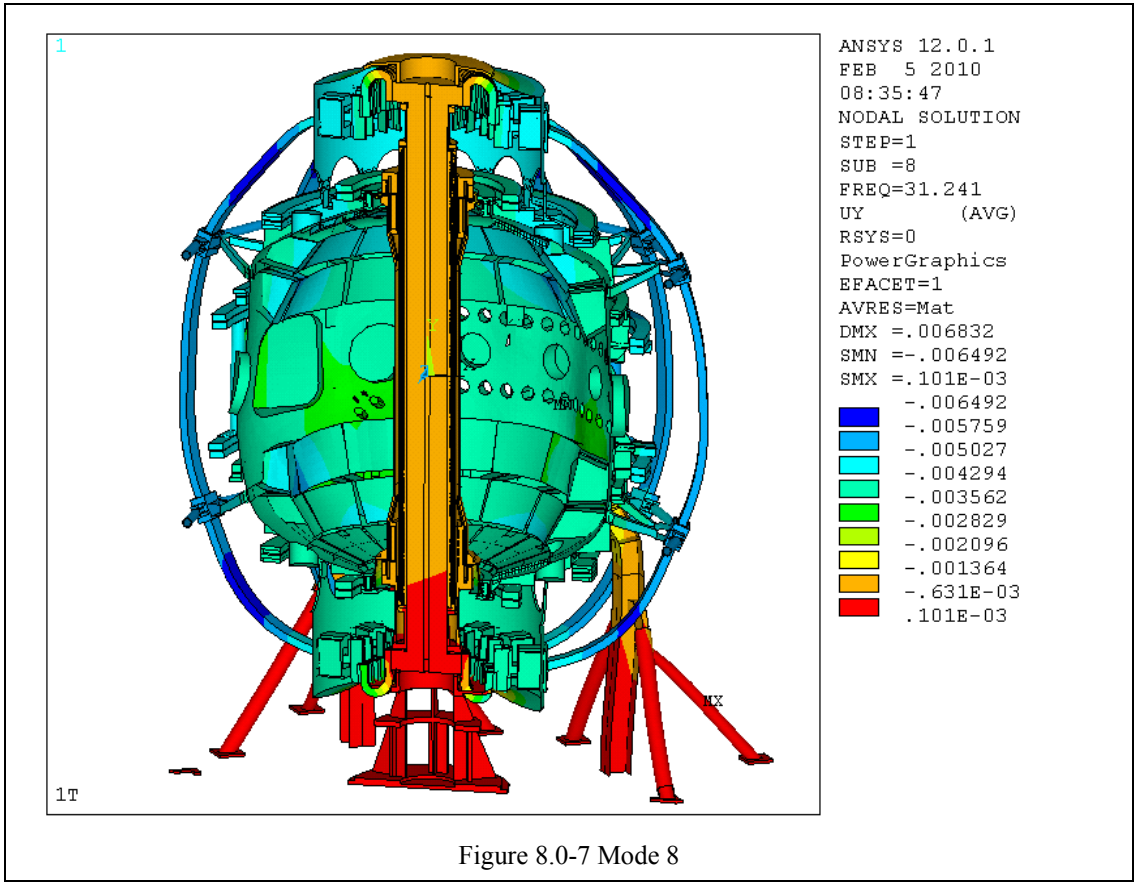
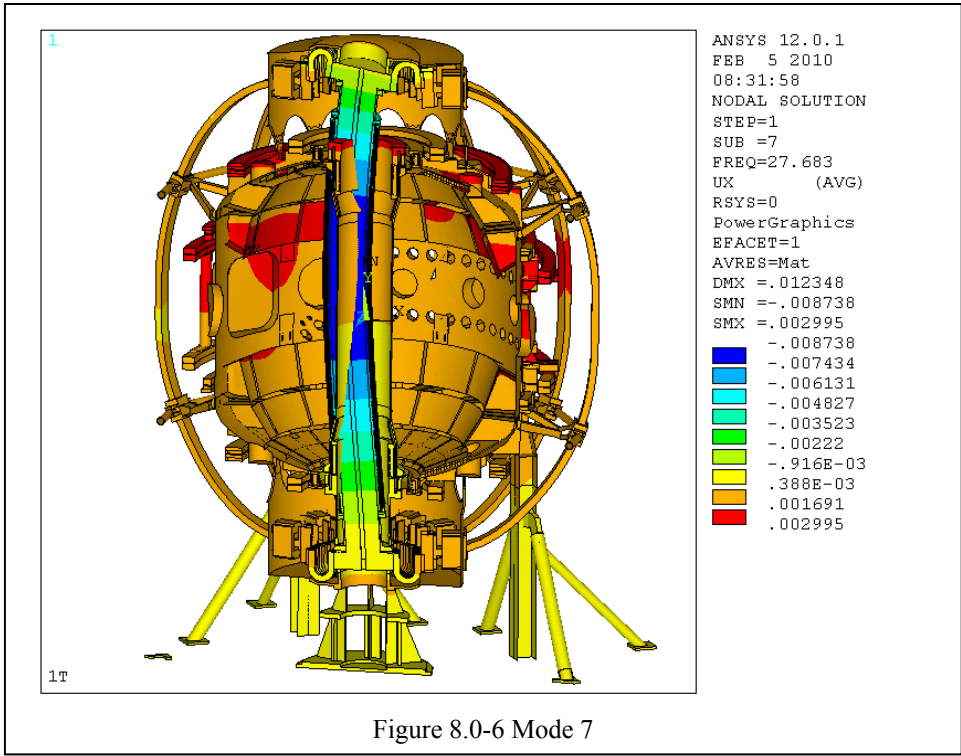
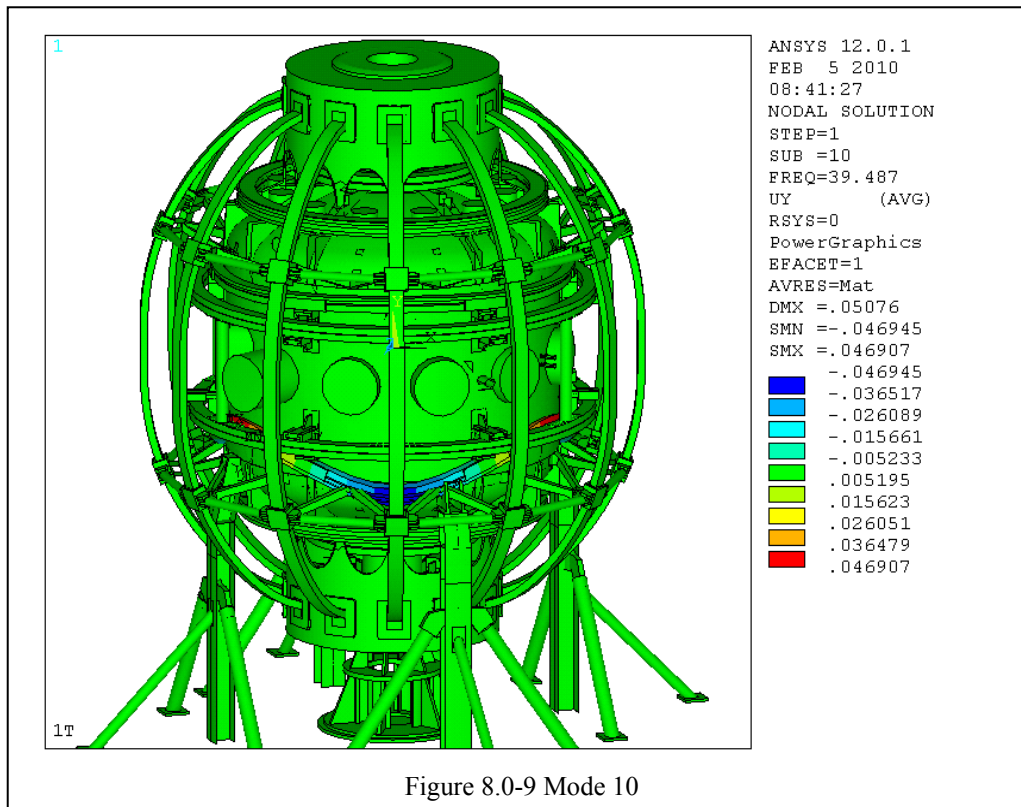
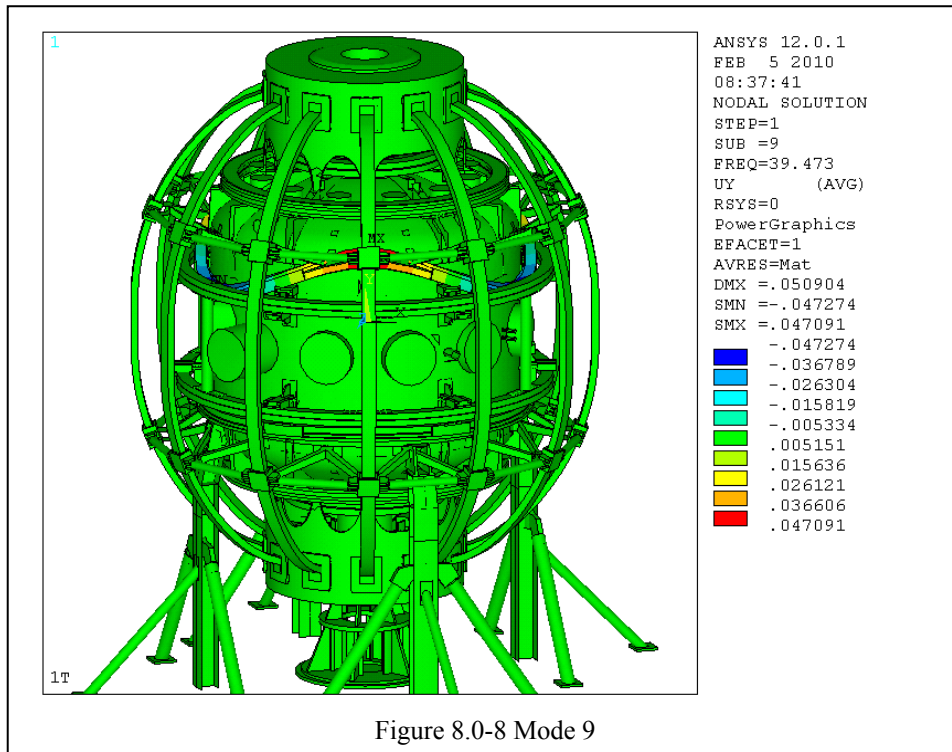


Figure 8.0-5 Mode 6





9.0 TF Loading Transient Analysis

9.1 Modal Analysis

TF Outer Leg Modes and Frequencies

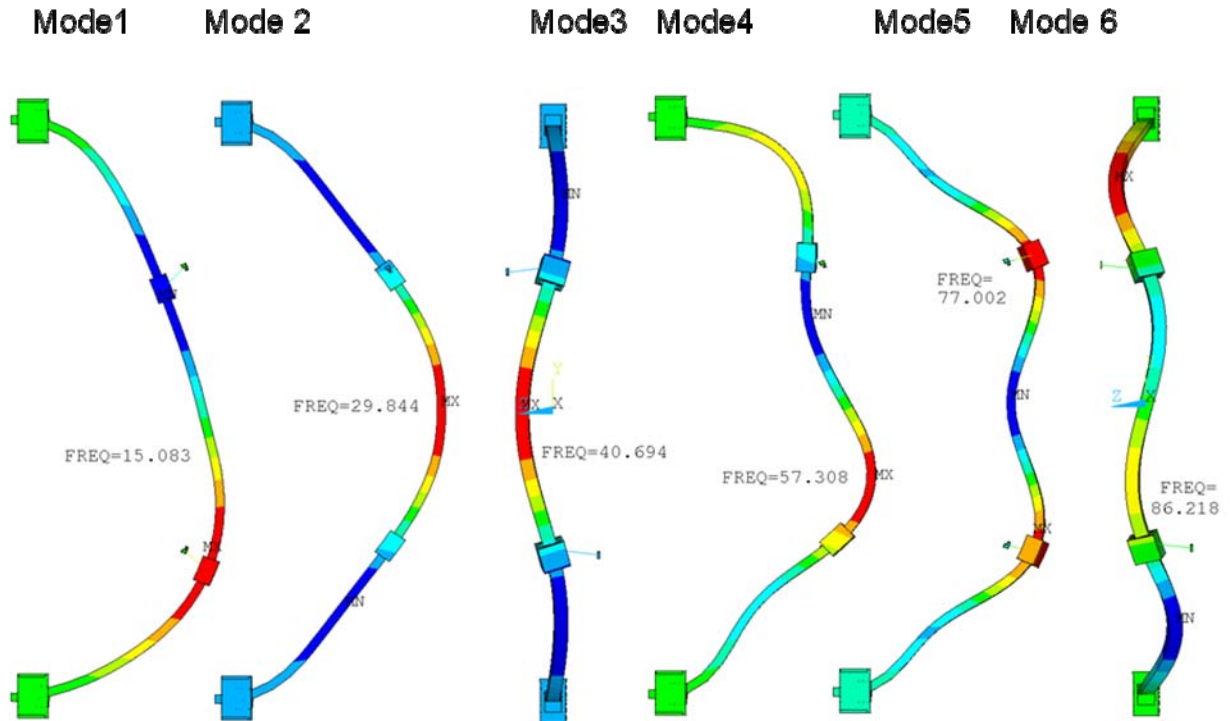


Figure 9.1-1 Outer Leg Frequencies and Mode Shapes. (Soft Spring)

9.2 Transient Analysis of OOP Loads

The batch file a right explored the effect of a soft radius rod connecting the TF at the knuckle clevis elevation. The command: $r,10,.001*.001$ input $.001*$ the radius rod assumed cross section of $.001 \text{ m}^2$

Damping Discussion from Ref [11]: Rayleigh damping constants α and β As Used in ANSYS

These are applied as multipliers of [M] and [K] to calculate [C]:

$$[C] = \alpha[M] + \beta[K]$$

$$\alpha/2\omega + \beta\omega/2 = \zeta$$

```

/batch
/prep7
et,1,45
et,8,8
ex,1,110e9 $dens,1,8000
$MP,PRXY, 1,0.3
ex,5,20e9 $dens,5,1000
$MP,PRXY, 5,0.3
ex,14,100e9 $dens,14,7000
$MP,PRXY, 14,0.3
ex,10,200e9 $dens,10,7000
$MP,PRXY, 10,0.3
/input,rad3,mod
/input,sing,mod
nummer,node,.001
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nelem
d,all,all
nall
eall
save
fini

```

```

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alphad, 5.0
betad, 5.3E-05
fscale,.0001,.0001
time,.0001
solve
save

*do,ld,1,1000
time,ld*.001
/input,sinf,mod
fscale,ld/1000,.00001
solve
save
*enddo
/input,sinf,mod
*do,ld,1,5000
time,1+ld*.001
solve
save
*enddo
fini
/exit

```


Where ω is the frequency, and ξ is the damping ratio. These are input in ANSYS in situations where damping ratio ξ cannot be specified. Alpha is the viscous damping component, and Beta is the hysteresis or solid or *stiffness* damping component.

Beta Damping As Used in ANSYS

Good for damping out high-frequency component-level oscillations (typically low amplitude). From Section 9.7 the first four modes of oscillation of the passive plates are : 191.9, 194.97, 205.33, 206.3 cps. Considering beta damping alone, and $\xi = .5\%$:

$$\beta = 2\xi/\omega$$

$$\beta = 2\xi/\omega = 2*.005/(30*2*3.1416) = 5.3E-05$$

This is small and is ignored in this calculation

Alpha Damping As Used in ANSYS

Alpha damping is also known as *mass damping*. It is Good for damping out low-frequency system-level oscillations (typically high amplitude).

If beta damping is ignored, α can be calculated from a known value of ξ (damping ratio) and a known frequency ω :

$$\alpha = 2\xi\omega$$

Only one value of alpha is allowed, the most dominant response frequency should be used to calculate α .

Considering Alpha damping alone, and $\xi = .5\%$:

$$\alpha = 2\xi\omega = 2*.005*30*2*3.1416 = 1.885$$

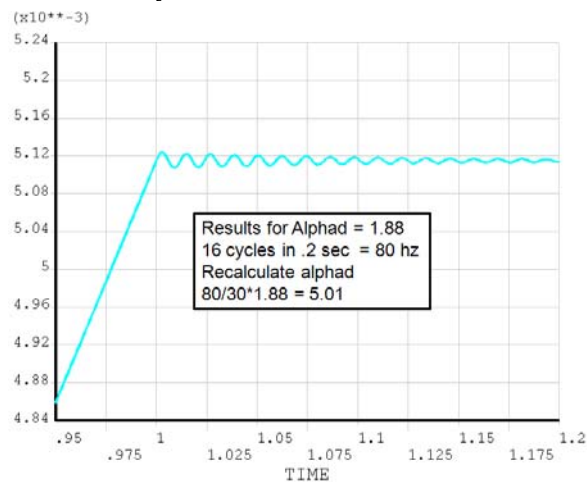


Figure 9.2-1 Stiff Spring Dynamic Results - Including Frequency Estimate - In Subsequent Runs use ALPHAD = 5.01

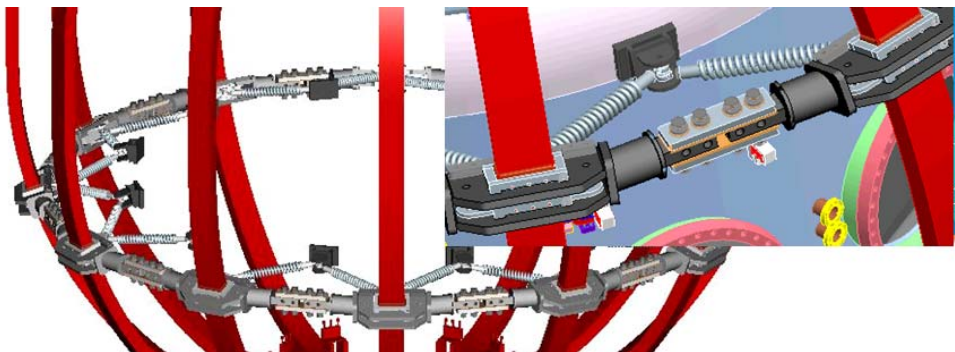


Figure 9.2-1 Soft Spring Truss Elements (PDR Design)

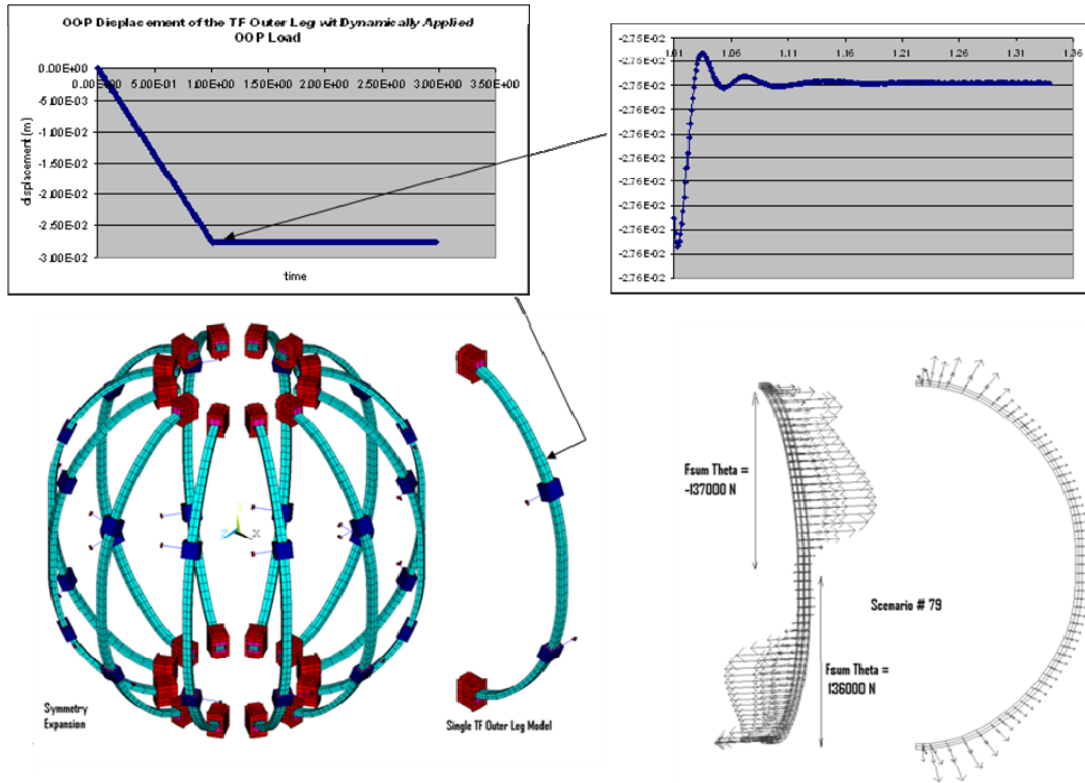


Figure 9.2-2 Outer Leg Transient Dynamic Analysis. (PDR Design, Soft Spring at the Vessel Knuckle)

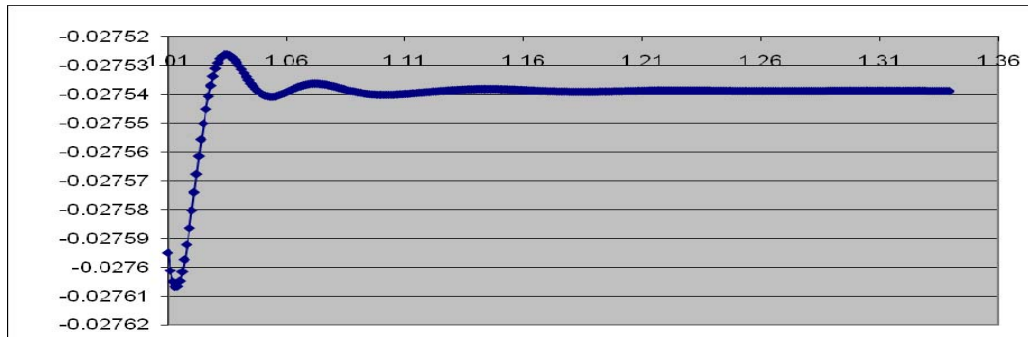


Figure 9.2-3 Enlargement of the transient portion of the curve

The simple single outer leg model allows a manageable transient time history analysis of the nominal pulse loading. In figure 9.1-2, the displacement results are plotted, first full scale, and second with a much expanded scale to show the over-shoot and oscillations of the coil. The stress in the coil would be linear with the displacement. These results are for a "Soft" truss rod that would limit loading at the Knuckle Clevis. This was the design in November of 2010. The oscillations have a relative magnitude of $.00012/.02754$ or .4%

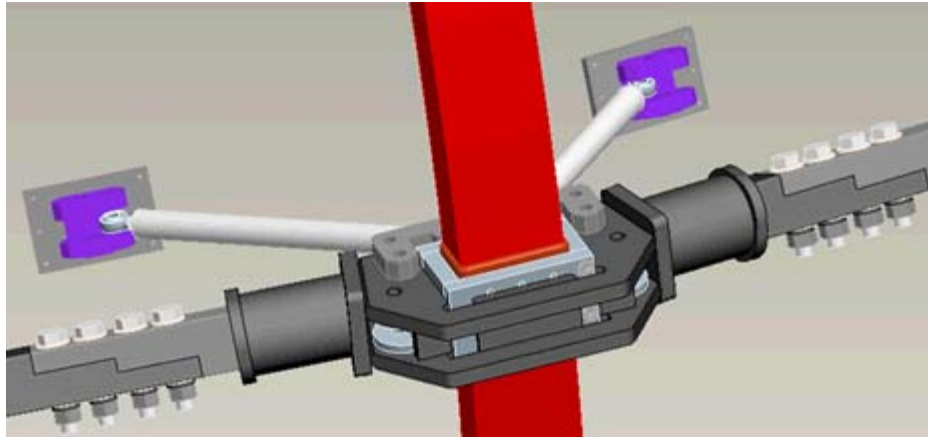


Figure 9.2-2 Solid Truss Elements (FDR Design)

The current (Sept 2011) design employs stiff truss rods and the frequency response is different than for the soft spring. Figure 9.2-3 shows the Out-of-Plane (OOP) displacement for the TF supported by stiff struts.

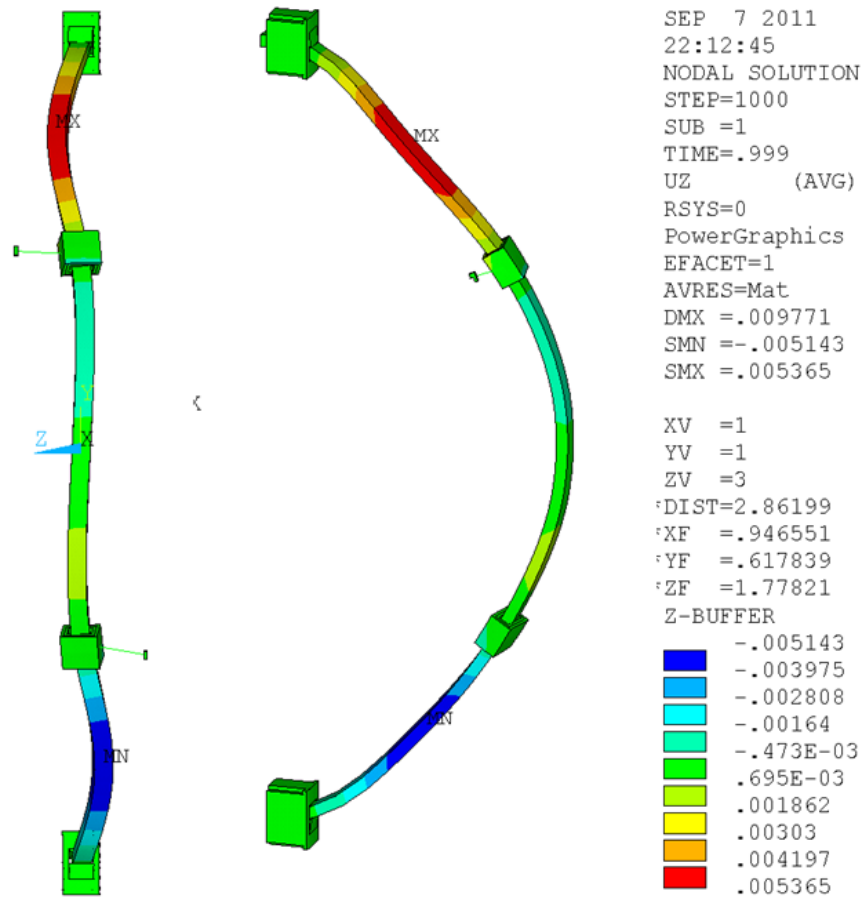


Figure 9.2-3 Out-of-Plane (OOP) Displacements

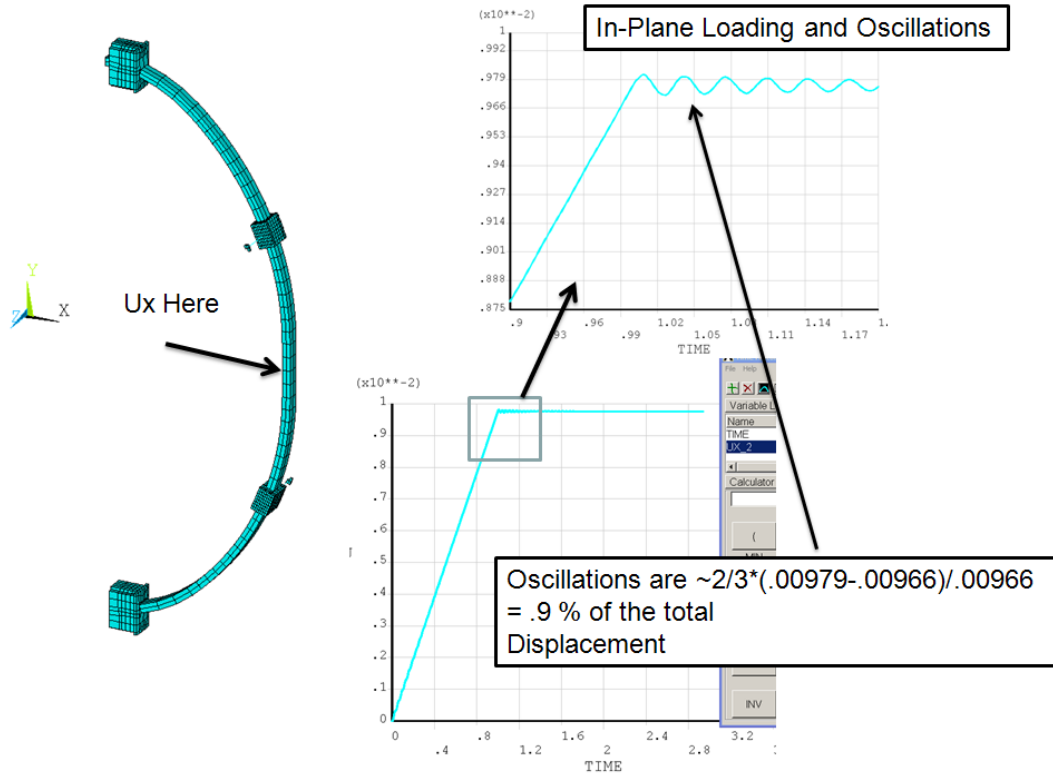


Figure 9.2-4 In-Plane Displacements

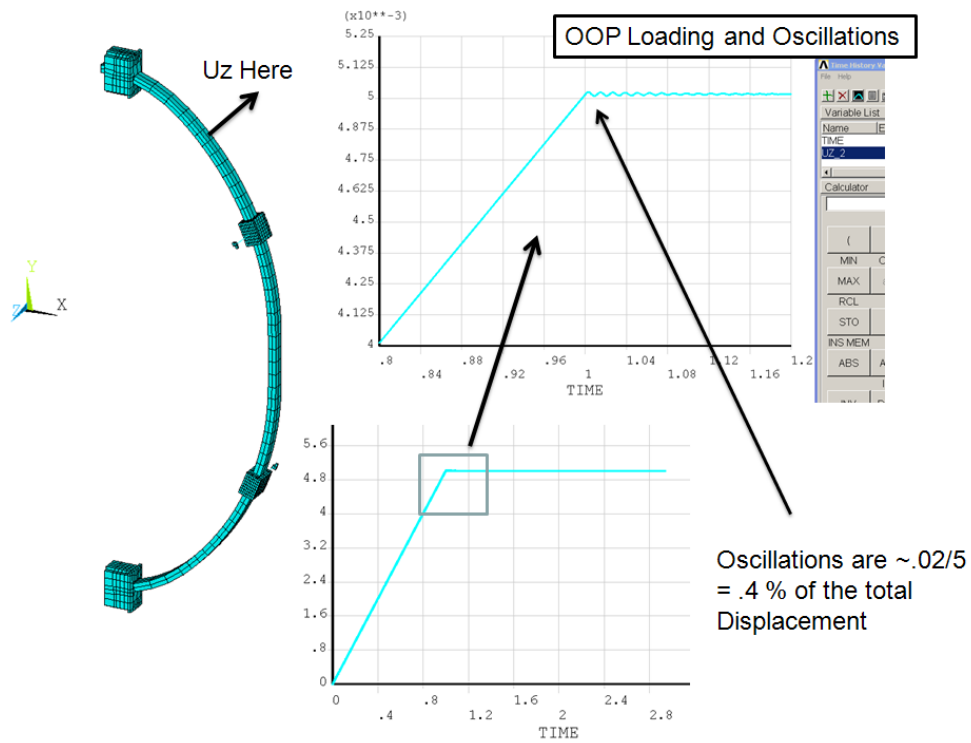


Figure 9.2-5 Out-of-Plane (OOP) Displacements

The oscillations represents an additional alternating stress component superimposed on the main stress component that results from the Lorentz loads, which for these cycles would be a mean stress.

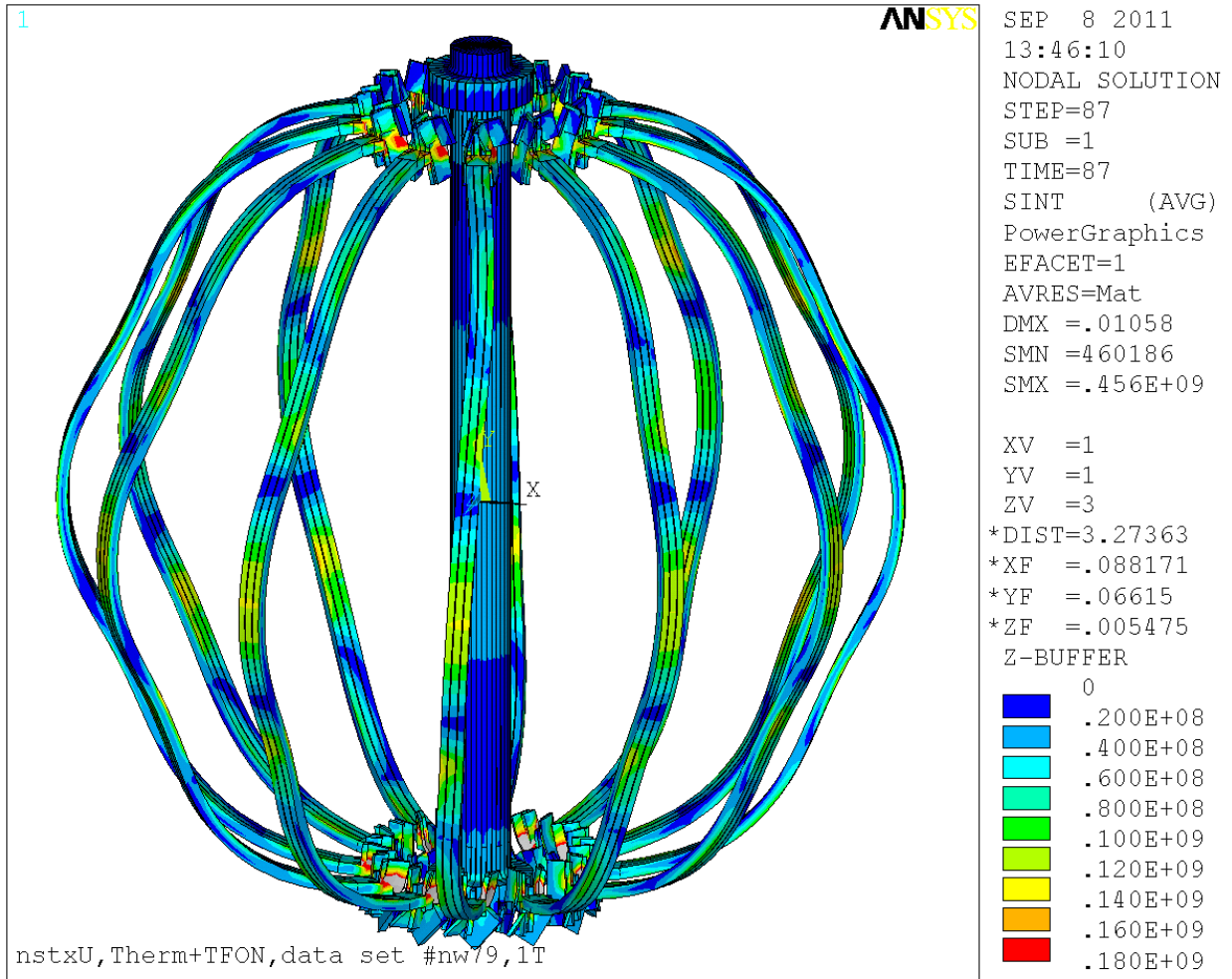


Figure 9.2-6 TF Tresca Stress for EQ #79 [2]

Use the Goodman equation [6] to calculate the increase in alternating stress due to the mean stress effect. At the mid-plane of the outer leg, the stress is 120 MPa. The tensile ultimate for the TF copper is 270 MPa. From the dynamic simulation for the radial mid-plane displacement, the oscillating component is .8% of the coil stress, or 0.96 MPa. With the mean stress effect included the equivalent alternating stress is : $.96/(1-120/270) = 1.72$ MPa. This level of stress would contribute no fatigue damage to the normal pulse loading cycles specified in the project GRD.

**Criteria Document [6]
Mean Stress Effect:**

$$Seq = \frac{Salt}{1 - (Smean/Su)}$$

where Su = tensile strength

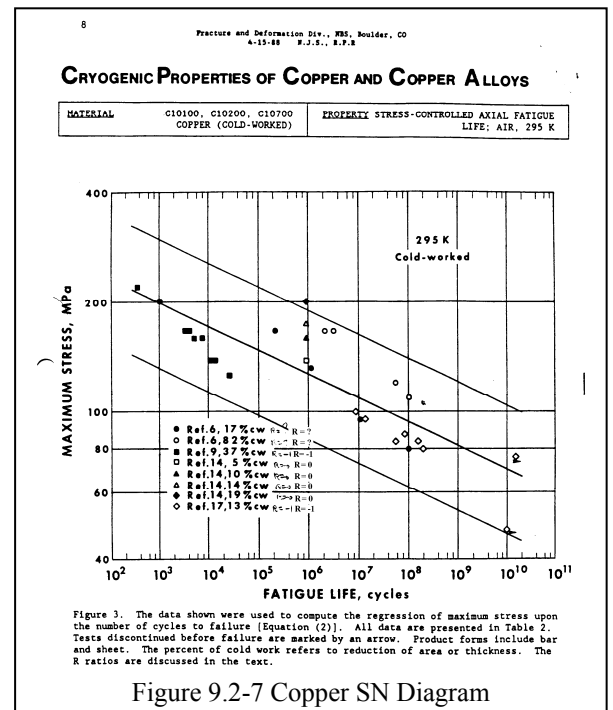


Figure 9.2-7 Copper SN Diagram

10.0 PF Loading Transient Analysis

PF stress oscillations from normal loading are also very small. The effect was shown to be trivial for the TF and will be trivial for the outer support details as well. Fundamental frequencies start around 73 Hz and are well above the frequency associated with the ramp-up. Reference [4] analysis model was used in this assessment.

```

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*do,imat,1,100
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dens,imat,8000
alpx,imat,17e-6
!r,imat,1.0e8
r,imat,1/.001/.001
*enddo
ex,90,1e6 $ex,3,20e9
ex,5,20e9 $ex,15,20e9
ex,6,2e6 $ex,7,2e6
ex,17,110e9
mu,6,.3
mu,5,.3
mu,15,.003
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/input,coia,mod
numner,node,.0002
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```

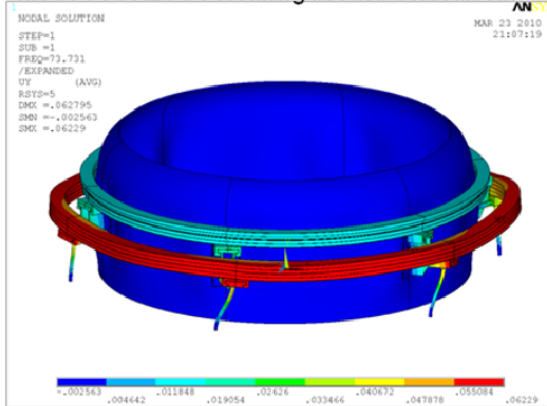
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d,all,uz,0.0 $d,all,uy,0.0
nall $eall
save
fini

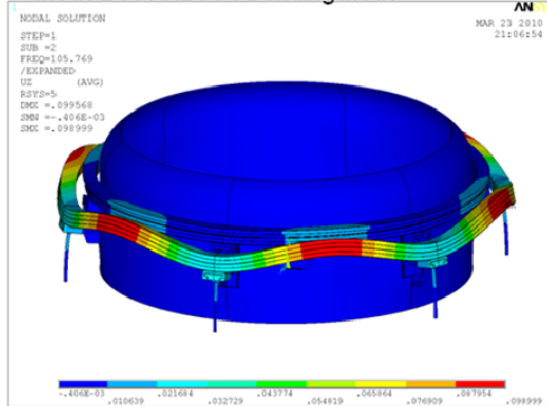
/solu
nsubst,1,1,1
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fscale,.0001
time,.0001
solve
save
*do,ld,1,1000
time,ld*.001
/input,coif,mod
fscale,ld/100
solve
save
*enddo
*do,ld,1,2000
time,1+ld*.001
solve
save
*enddo
fini $/exit

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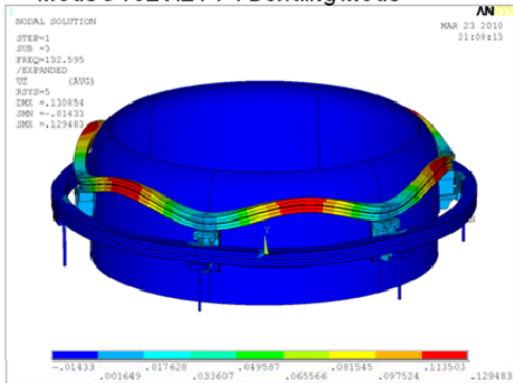
Mode 1 73 Hz PF5 Rotating about a Vertical Axis



Mode 2 105 Hz PF5 Bending Mode



Mode 3 132 Hz PF4 Bending Mode



Mode 4 156 Hz PF4 Radial Oscillation

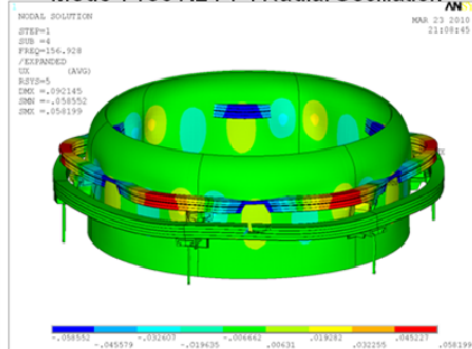


Figure 10.0-1 Outer PF Support Mode Shapes.

PF 4/5 Dynamic Response to a Transient Load Application

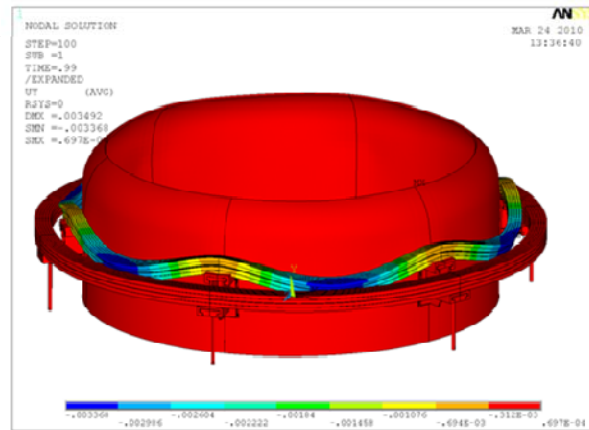
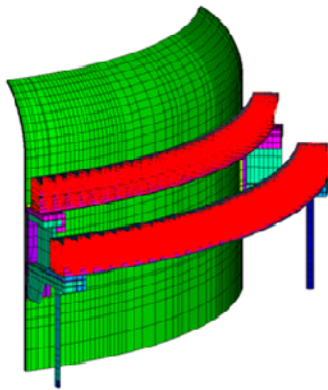
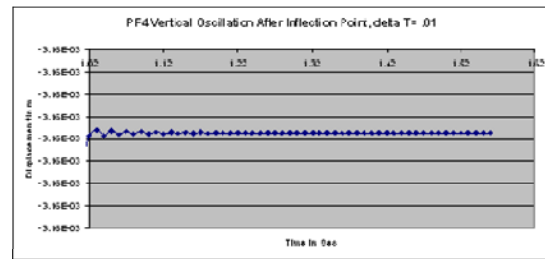
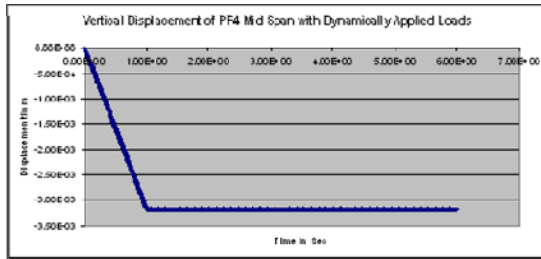


Figure 10.0-2 Outer PF Support Transient Dynamic Results.