NSTXU-CALC-55-11 Rev 0, March 14 2018

Title: Calculation of Suppress and Bypass Coil and Bus Dynamic Structural Response

Purpose of Calculation:

The purpose of this calculation is to quantify the dynamic response to a suppress and bypass initial over-current. This effect is evaluated for a typical (PF1aU) bus bar response and the response of the coil to the current increase over the nominal operating current as the coils are shut down. The intention of this calculation is to determine if the overcurrent loading from the suppress and bypass must additionally address a dynamic increase from the mechanical response.

Codes and versions: ANSYS Version 15

References:

Included in the body of the calculation section 6.1

Assumptions:

The bus bar model used in this analysis is representative of the terminal and bus designs as they were used in the 2016 run. The purpose of this calculation is to develop dynamic load factors for application to other similar terminal and bus analysis and the local detail difference should not significantly alter the dynamic increase in loads. The structural frequency is of the form SQRT(stiffness/mass) and the square root diminishes the effect of stiffness and mass which should be similar for all 6 bus and terminal configurations. Similarly, the response of PF1a is assumed adequately representative of all the inner PF coils

Calculation:

See Body of the Calculation

Conclusion:

The 5% and .5% damped cases for the coil response and the bus bar response, produce almost no amplification. Evaluation of the coils and bus bars can be based on a static structural assessment of the current overages supplied by C. Neumeyer and Andy Gao. There is some concern that the damping is over estimated, and some clarification of the damping calculation is presented in Appendix C, however the conclusion that the DLF, is not needed is not altered.

Cognizant Individual (or designee) printed name, signature, and date
Steve Raftopoulos”

Steve Raftopoulos
Digitally signed by Steve Raftopoulos
Date: 2018.09.18 10:23:38 -04'00'

Preparer’s printed name, signature and date
Peter Titus:

Peter H. Titus
Digitally signed by Peter H. Titus
Date: 2018.09.18 09:04:17 -04'00'

I have reviewed this calculation and, to my professional satisfaction, it is properly performed and correct. Checker’s printed name, signature, and date
Han Zhang:

Han Zhang
Digitally signed by Han Zhang
Date: 2018.09.18 11:10:54 -04'00'

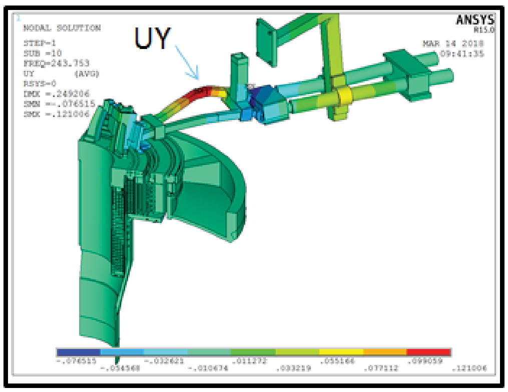
National Spherical Torus eXperiment - Upgrade

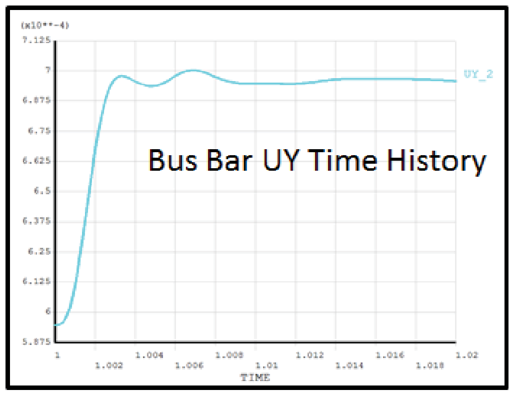
NSTX-U

Calculation of Suppress and Bypass Coil and Bus Dynamic Structural Response

NSTXU-CALC-55-11

March 14 2018





Peter H. Titus
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Date: 2018.03.28 16:28:11 -04'00'

Prepared By
Peter Titus

Han Zhang
Digitally signed by Han Zhang
Date: 2018.03.28 17:01:11 -04'00'

Reviewed By
Han Zhang

Steve Raftopoulos
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Date: 2018.03.29 13:22:54 -04'00'

Approved By – Responsible Engineer
Steve Raftopoulos

- NSTX-U CALCULATION

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- 1.0 Table of Contents

NSTX-U CALCULATION

Record of Changes

Rev.	Date	Description of Changes	Revised by
0	10/20/16	Initial Release	

ENG-33 Calculation Form

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References:

Included in the body of the calculation

Assumptions:

The bus bar model used in this analysis is representative of the terminal and bus designs as they were used in the 2016 run. The purpose of this calculation is to develop dynamic load factors for application to other similar terminal and bus analysis and the local detail difference should not significantly alter the dynamic increase in loads. The structural frequency is of the form SQRT(stiffness/mass) and the square root diminishes the effect of stiffness and mass which should be similar for all 6 bus and terminal configurations. Similarly, the response of PF1a is assumed adequately representative of all the inner PF coils

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See Body of the Calculation

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The 5% and .5% damped cases for the coil response and the bus bar response, produce almost no amplification. Evaluation of the coils and bus bars can be based on a static structural assessment of the current overages supplied by C. Neumeyer and Andy Gao. There is some concern that the damping is over estimated, and some clarification of the damping calculation is presented in Appendix C, however the conclusion that the DLF, is not needed is not altered.

6.0 Design Input
6.1 References

[1] Calculation of Suppress/Bypass Shutdown Currents For Inner PF Coils NSTXU-CALC-52-01-00, C. Neumeyer March 2018
[2] Calculation of PF 1aU Flex Bus Analysis Rev 1 (2016 Run Configuration) NSTXU-CALC-55-03-1 March 2018
[3] Design Point Spreadsheet Calculations for NSTX Center Stack Upgrade, NSTX-U-CALC-10-03-00

6.2 Requirements from Electrical Simulation

The input for this calculation is the suppress and bypass electrical simulation by Neumneyer and Gao [1] A table summary of results is presented below:

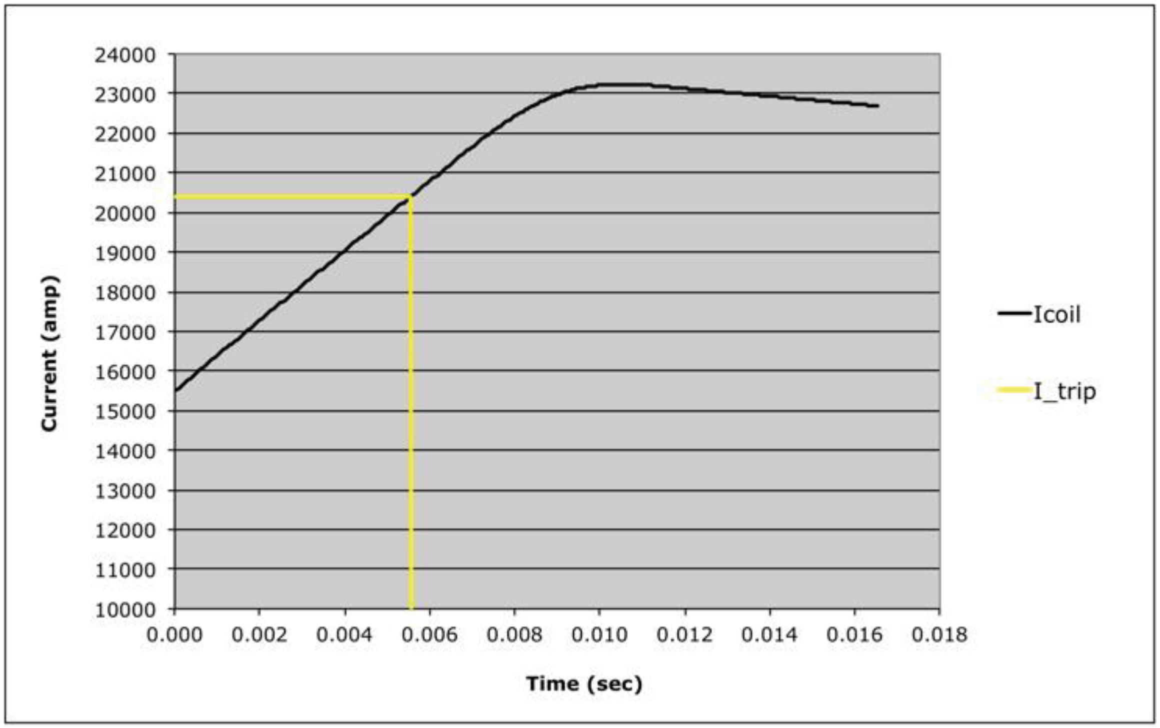
Table 1 – Suppress/Bypass Transient Cases

Coil	PF1A		PF1B		PF1C		
Irated	20000	20000	21000	21000	20000	20000	Amp
Headroom multiplier	1.02	1.05	1.02	1.05	1.02	1.05	
Itrip	20400	21000	21420	22050	20400	21000	Amp
Lcoil	1.84E-03	1.84E-03	4.45E-04	4.45E-04	4.57E-04	4.57E-04	Henry
Rcoil	5.93E-03	5.93E-03	9.19E-03	9.19E-03	4.49E-03	4.49E-03	Ohm
Lclr	2.72E-04	2.72E-04	2.72E-04	2.72E-04	2.72E-04	2.72E-04	Henry
Rclr	1.00E-03	1.00E-03	1.00E-03	1.00E-03	1.00E-03	1.00E-03	Ohm
Lext	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	Henry
Rext	2.00E-03	2.00E-03	2.00E-03	2.00E-03	2.00E-03	2.00E-03	Ohm
Ltot	2.11E-03	2.11E-03	7.17E-04	7.17E-04	7.29E-04	7.29E-04	Henry
Rtot	8.93E-03	8.93E-03	1.22E-02	1.22E-02	7.49E-03	7.49E-03	Ohm
dI_blip ~ (V-I*R)*dt/L	2851	2837	2882	2822	3660	3626	Amp
dI_blip	2843	2840	3027	2984	3668	3648	Amp
Imax	23243	23840	24447	25034	24068	24648	Amp

The coil hoop stress is driven by its self -load and will scale as the square of the current ratio. ,The terminal and bus loads are driven mainly by the terminal current crossing the toroidal field. So these loads will scale linearly with the coil current ratio.

Cur Ratio	1.16215	1.192	1.164143	1.192095	1.2034	1.2324
Coil Load Ratio	1.350593	1.420864	1.355229	1.421091	1.448172	1.51881
Terminal and Bus Ratio	1.16215	1.192	1.164143	1.192095	1.2034	1.2324

The 16% PF1a overcurrent case was chosen for analysis. The results will be a dynamic load factor that can be applied to the 19% case and to the other coils approximately.



PF1aU Current Trace from Ref [1]

6.3 PF1a Loading from Overcurrents

C. Neumeyer and Andy Gau produced a table of peak currents vs. nominal current from the suppress and bypass over-current simulations [1]. For the self coil loading, the loads increase as the square of the current. To check the structural response of the coil, the nominal loading is multiplied by the square of the ratio of over-current. A time transient analysis is then performed with a load profile that simulated the transient electrical response..

Cur Ratio	1.16215	1.192	1.164143	1.192095	1.2034	1.2324
Coil Load Ratio	1.350593	1.420864	1.355229	1.421091	1.448172	1.51881
Terminal and Bus Ratio	1.16215	1.192	1.164143	1.192095	1.2034	1.2324

7.0 Analysis Models

Two models are used in the analysis. The first is a 2D axisymmetric model of the machine cross section in which the Lorentz loads from all the equilibrium can be applied. For this analysis EQ 51 is used. The loading from EQ51 is scaled to produce a time history of loading consistent with the magnitude and frequency of the overcurrent loading. The loads are calculated outside ANSYS in a simple elliptic integral code. The second model is a model used to qualify the bus used in the 2016 run. This model is documented without the col in rev0 of [2] and with the coil in rev 1 of [2] It is shown in figure 7.0-3

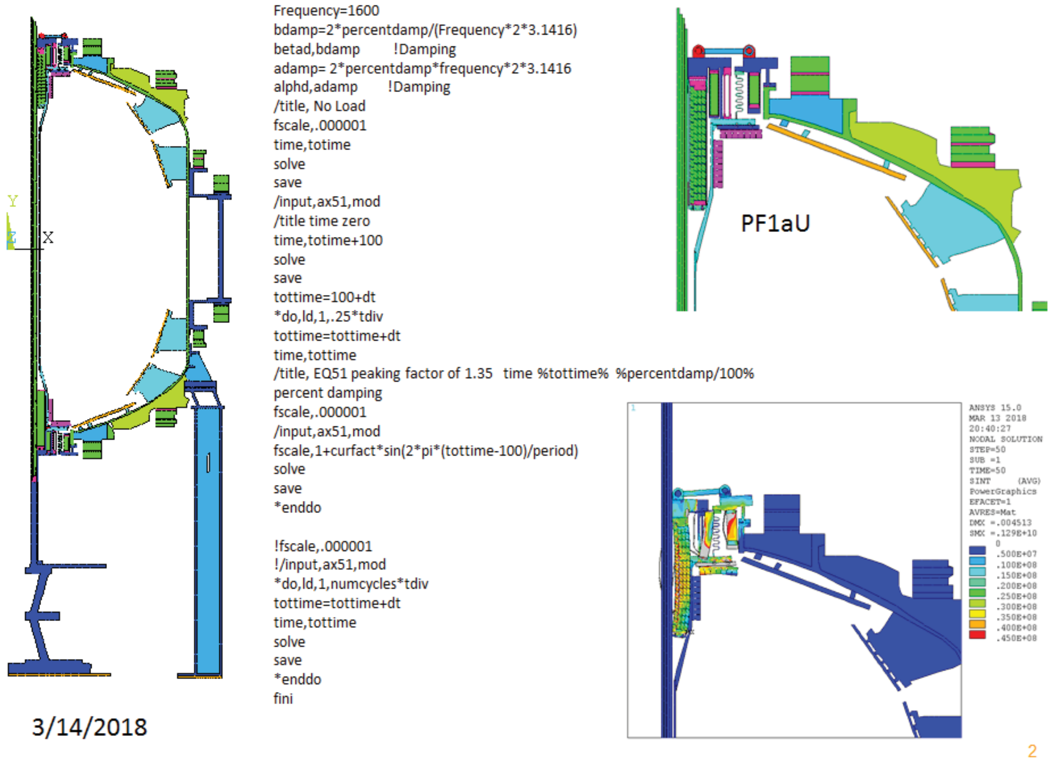


Figure 7.1 Axisymmetric model and a Typical Stress Plot from the Transient

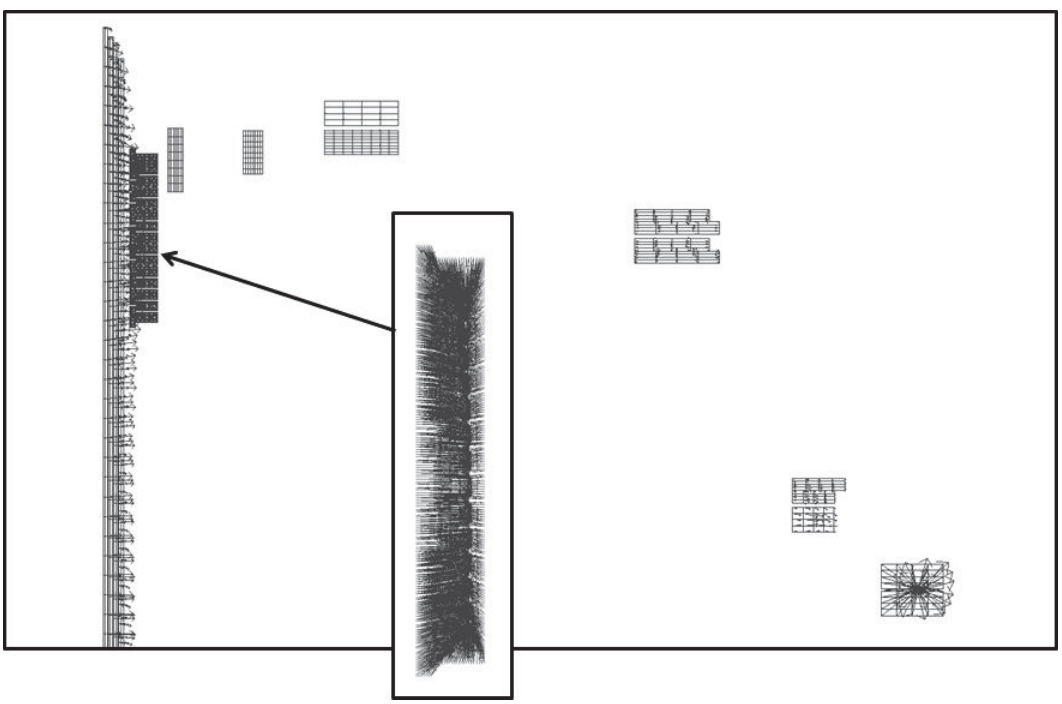


Figure 7.2 Lorentz Forces on PF1aU

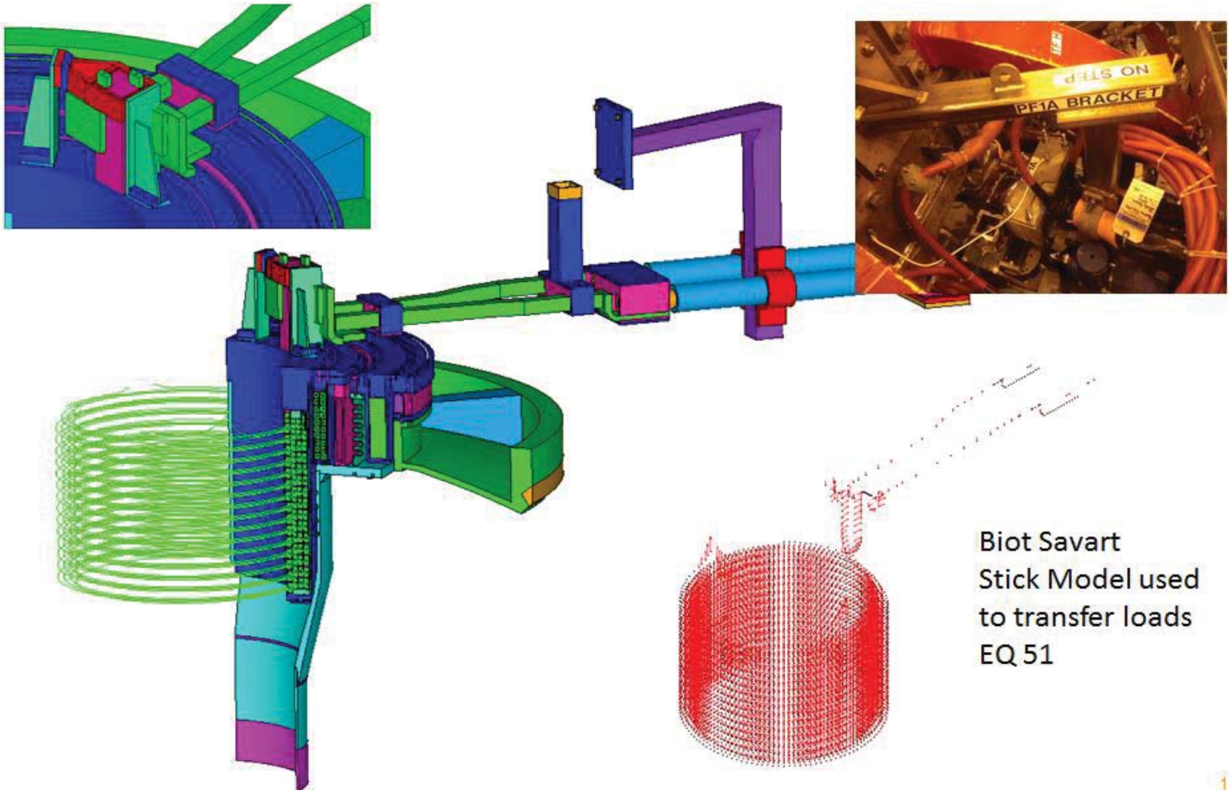


Figure 7.3 Upper PF1a Coil,Terminal,Bus Model

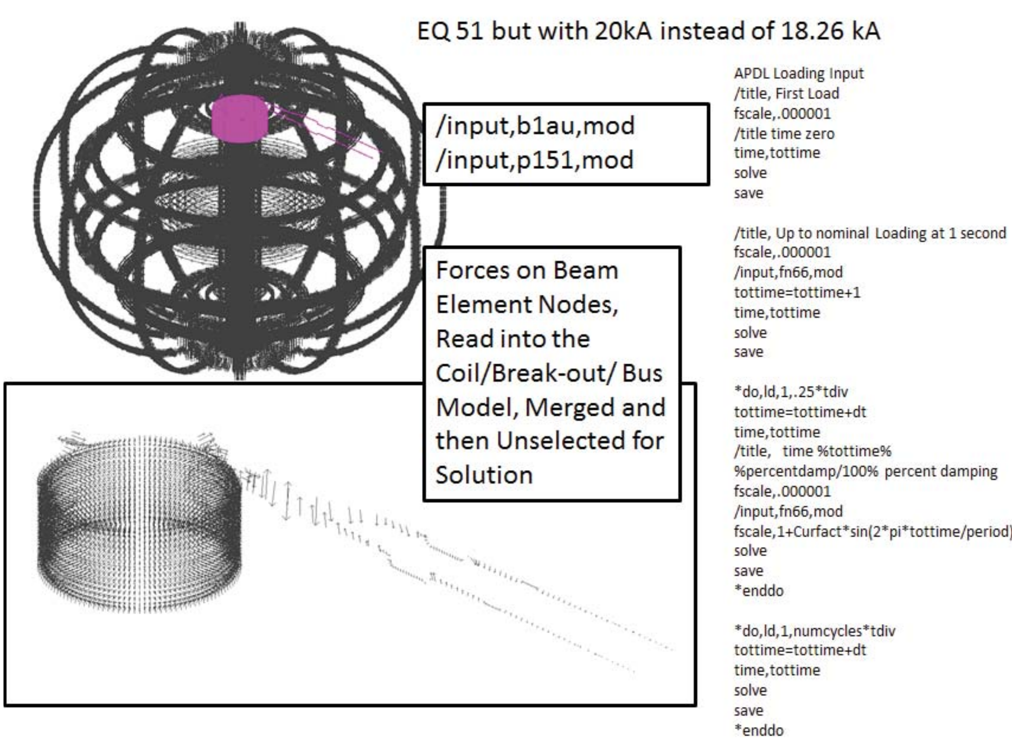


Figure 7.4 Biot Savart Calculation of the Force File APDL Script for it Application in a Structural Transient of the 3D model of PF1a Coil/Terminal/and Bus

8.0 Results of the Axisymmetric Transient Analysis of PF1aU EQ 51 Loading with Suppress and Bypass Overcurrents

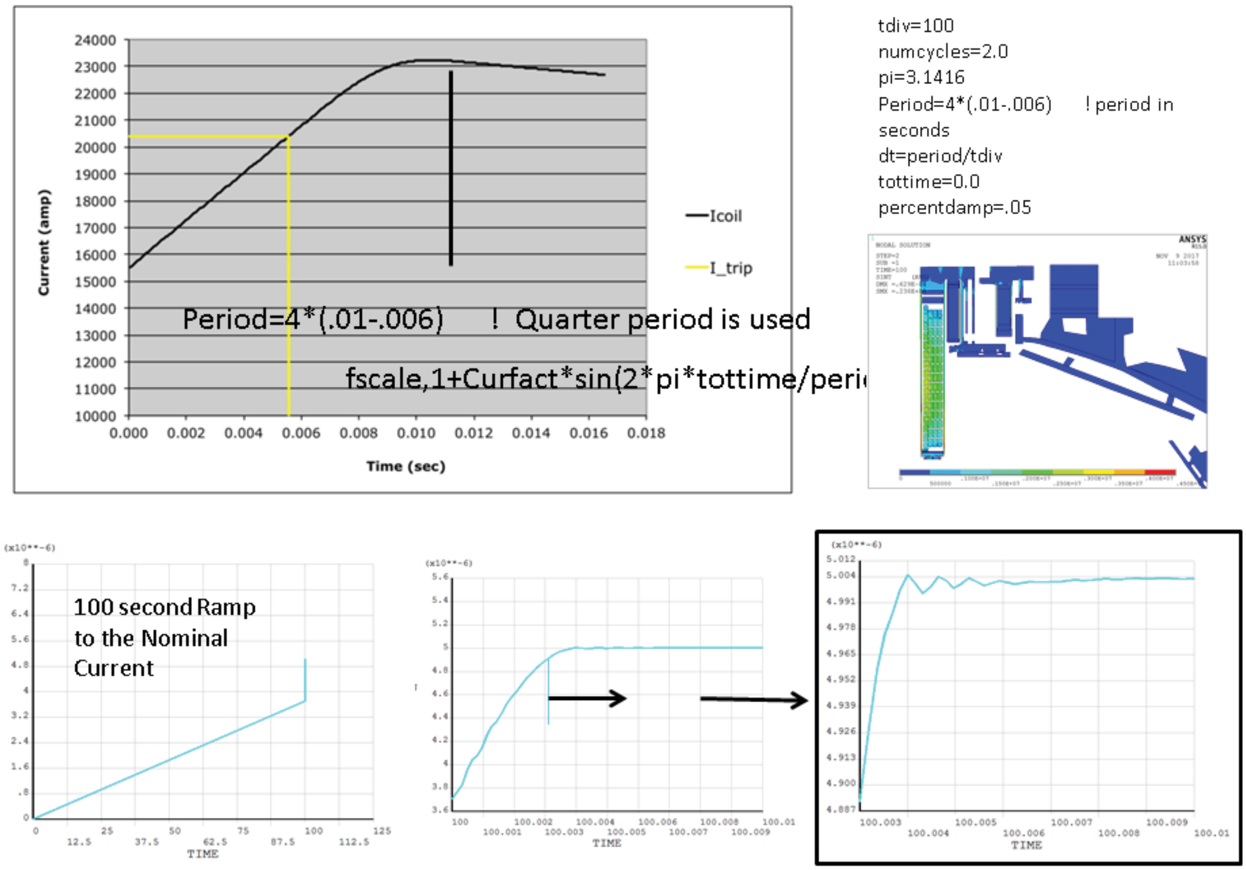


Figure 8.0-1 Displacement Time Transients of the Radial motion pf PF1aU for 5% Damping

The results for the 5% damping case showed no dynamic amplification. To test whether the damping was excessive ,a .5% damping case was run. While the effect of the reduced damping was evident, the dynamic response was still minor. Note the oscillations of the coil in te magnified frame shows a frequency around 1700 hz

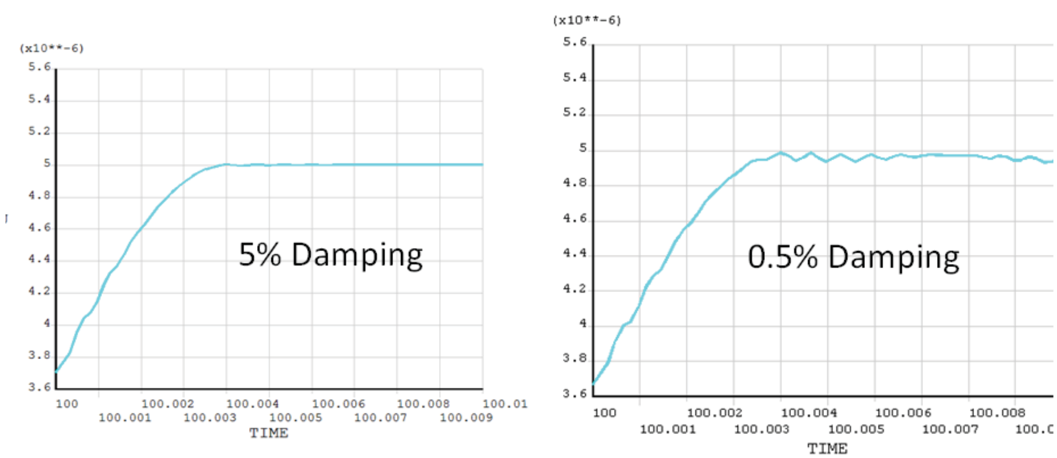


Figure 8.0-2 Time Transients of the Radial motion pf PF1aU for 5% and .5% Damping

9.0 Bus Bar Response to Suppress and Bypass Over-Currents

The bus bar model from the 2016 run campaign is representative of the recovery model – at least to quantify a dynamic load factor to apply to other bus and terminal models to address the dynamics of the suppress and bypass overcurrent. The response of the displacement of the 1.5 in square bare is taken as indicative of the dynamic response of the terminal/bus system. In figure 9.0-1

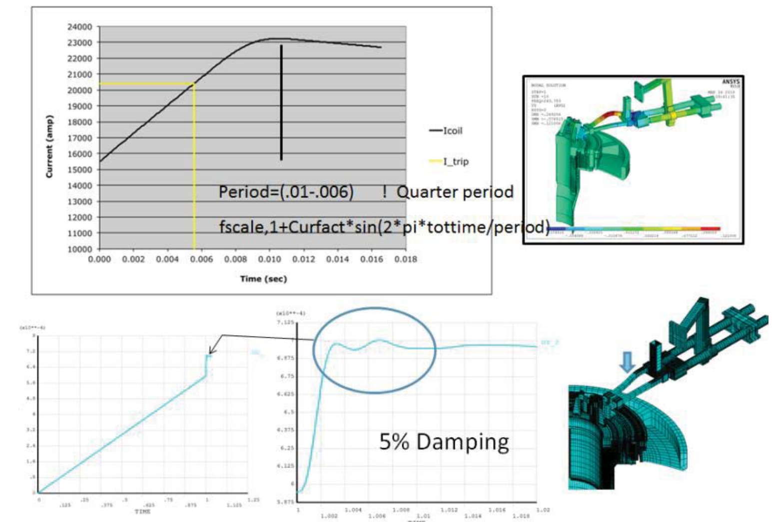


Figure 9.0-1 Dynamic Response of the Terminal/Bus System to the Suppress and Bypass Loading

An estimate of the dynamic load factor is accessible by considering the response of single degree of freedom oscillators to forcing functions with varying frequencies. In Figure 9.0-2 this is presented in Figure 9.0-2. The results of a mode-frequency analysis is presented with the fundamental mode of the bar flexure being 243 hz

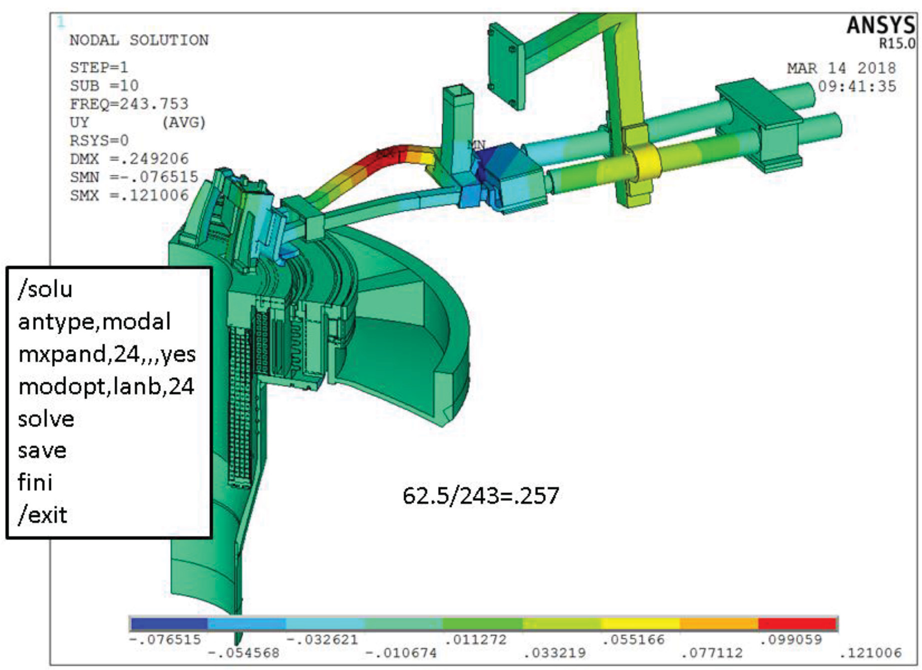


Figure 9.0-2 Frequency of the Bus Bar Bending Mode and the response of a single degree of freedom Oscillator to forcing functions of varying frequency.

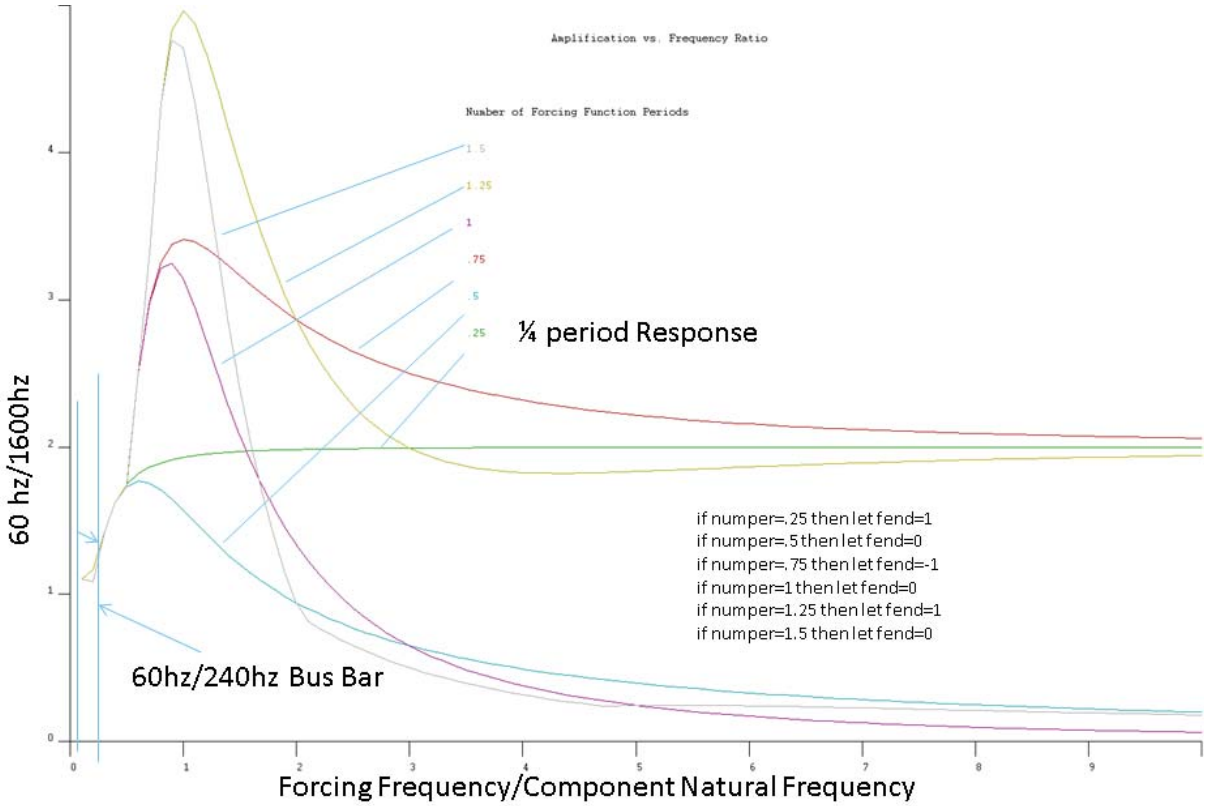


Figure 9.0-3 Amplification vs Frequency Ratio for a Set of Single Degree of Freedom Oscillators

The frequency of the bus bar is needed for the damping calculations and to do a sanity check comparison of the amplification with respect to the frequency of the forcing function. The forcing function is s quarter wavelength with a period of 4*.004 = .106. The frequency is then 1/.016=62.5 hz. Figure 9.0-2 above shows the frequency of the bus bar bending of 243 hz, so the bus bar is rigid with respect to the forcing function, and very little amplification is expected. The Amplification vs Frequency Ratio is shown in figure 9.0-3. In the figure above, the bus bar and the hoop response in the static region of the curves.

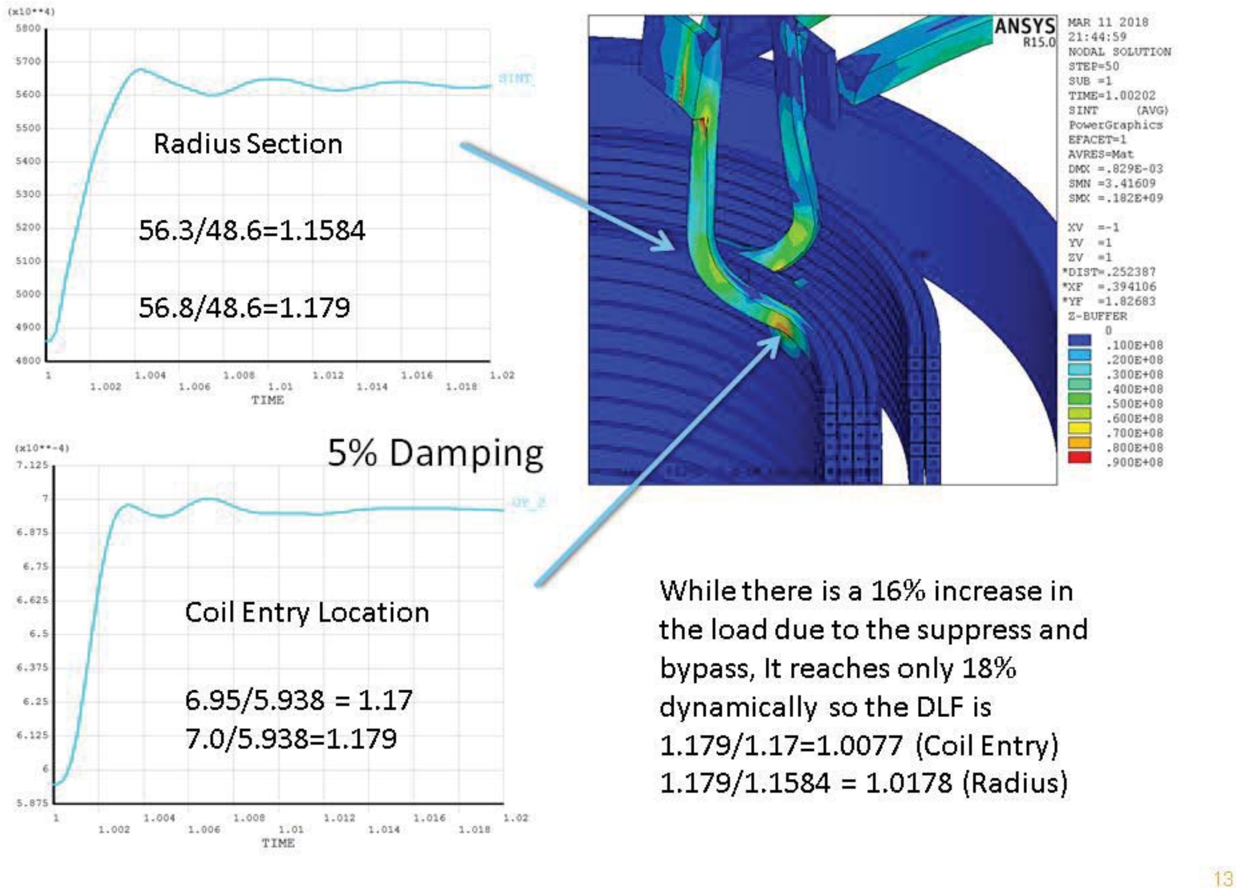


Figure 9.3 Break-Out and Terminal Stress Dynamic Response

Another critical location in the terminal area is the break-out from the coil winding where there are bending stresses, principally resulting from currents crossing the toroidal field. In these areas the dynamic load factors are close to 1.0

Appendix A PF1a Bus Bar Transient ANSYS Listing

```
/batch
/filnam,trans
/prep7
/NERR,100000,100000
runn=1
tdiv=100
numcycles=2.0
pi=3.1416
Period=.004      ! millisec per megamp this is the period of the disruption  excitation
dt=period/tdiv
tottime=0.0
percentdamp=.05
et,1,45
et,2,52
et,99,45
et,152,63
et,4,4
r,1,1e6
r,2,1e7,,0.0
r,10,1e6
r,63,1,1,1,1,1,1,1,1,1,1,1,1
*do,imat,1,100
ex,imat,200e9
dens,imat,7900
alpx,imat,17e-6
*enddo
ex,3,117e8
!ex,12,117e9    ! This is the Inconel Case
ex,17,117e9
ex,7,20e9             !Flex Cable and Conductor Hole
ex,77,20e9
ex,4,117e9            !Outer Cable Wrap
ex,8,1e9
ex,15,117e9
ex,5,20e9

   ! Mat,57 is CTD 425 in the horizontal reinforcement direction
ex,57,5.714e9
ey,57,4e9
ez,57,5.714e9
gxy,57,2.2857e9
gyz,57,2.2857e9
gxz,57,2.2857e9
nuxy,57,.17
nuyz,57,.33
nuxz,57,.33
alpx,57,28e-6
alpy,57,10.33e-6
alpz,57,10.33e-6

   ! Mat,56 is CTD 425 in the vertical reinforcement direction
ex,56,4e9
ey,56,5.714e9
ez,56,5.714e9
gxy,56,2.2857e9
```

```
gyz,56,2.2857e9
gxz,56,2.2857e9
nuxy,56,.33
nuyz,56,.17
nuxz,56,.33
alpx,56,28e-6
alpy,56,10.33e-6
alpz,56,10.33e-6

ex,41,117e9
alpx,10,13.3e-6
mptemp,,80,130,180,290,1000

!Mat 6, Copper
*do,imat,6,6,1
mpdata,kxx,imat,1,192.76302,167.98521,167.98521,167.98521,167.98521
mpdata,rsvx,imat,1,.218e-8,.572e-8,.925e-8,1.703e-8,2.480e-8
mpdata,rsvy,imat,1,.218e-8,.572e-8,.925e-8,1.703e-8,2.480e-8
mpdata,rsvz,imat,1,.218e-8,.572e-8,.925e-8,1.703e-8,2.480e-8
mpdata,c, imat ,1, 86.092418 , 130.18853 , 145.3072 , 161.2658 , 166.30535
mp,dens,imat,8950
ex,imat,117e9
pf=1.0
alpx,1,17e-6
pex=118660e6
EX, imat , pex
NL, imat ,13,17
NL, imat ,14, .0001 , .001 , .002 , .007 , .04
NL, imat ,19,4, pex*.0001  , pf*51.49186e6 , pf*72.61814e6 , pf*103.30089e6 , pf*123.98589e6,pf*140e6
NL, imat ,25,77, pex*.0001  , pf*46.34819e6 , pf*64.30277e6 , pf*91.04158e6 , pf*109.28575e6,pf*110e6
NL, imat ,31,292, pex*.0001  , pf*31.59289e6 , pf*42.51457e6 , pf*59.76586e6 , pf*71.88727e6 ,pf*80e6
NL, imat ,37,700, pex*.0001   , pf*12.5489e6 , pf*16.56179e6 , pf*23.37405e6 , pf*28.36603e6 ,pf*33e6
NL, imat ,43,900, pex*.0001  , pf*9.1014e6 , pf*12.06625e6 , pf*17.19613e6 , pf*21.00217e6 ,pf*24e6
NL, imat ,49,1000, pex*.0001  , pf*8.92213e6 , pf*11.92835e6 , pf*17.18234e6 , pf*21.12628e6 ,pf*22e6
nuxy,imat,.3
*enddo
/input,b1au,mod
/input,pn66,mod
nummer,node,.00003
esel,mat,11
nelem
nummer,node,.0003
nall
eall
csys,5
nrotate,all
nsel,y,-46,-44
d,all,uy,0.0
nsel,y,44,46
d,all,uy,0.0
esel,mat,40
nelem
d,all,all,0.0
esel,mat,41
nelem
d,all,uy,0.0
```

```
d,all,ux,0.0
d,all,uz,0.00                    !1
nall
eall
tref,292
tunif,292
eusel,type,4
eusel,type,152
nelem
save
fini
!/exit

/solu
antype,trans
tunif,292
tref,292
!nlgeo,on

Frequency=100
bdamp=2*percentdamp/(Frequency*2*3.1416)
betad,bdamp         !Damping
adamp= 2*percentdamp*frequency*2*3.1416
alphd,adamp        !Damping


/title, First Load
fscale,.000001
/title time zero
time,totime
solve
save

*do,ld,1,.5*tdiv
tottime=tottime+dt
time,tottime
/title,   time %tottime%  %percentdamp/100% percent damping
fscale,.000001
/input,fn66,mod
fscale,sin(2*pi*tottime/period)
solve
save
*enddo

fscale,.000001
*do,ld,1,numcycles*tdiv
tottime=tottime+dt
time,tottime
solve
save
*enddo


/exit
```

Appendix B
DLF Program with Sustained loading at end of forcing function

```
set color "white"
let numper=1
! m is unity
!freq=1/2/pi*(k/m)^.5
!freq^2=1/4/pi^2*(k/m)
let freq=10
let ffreq=100
set window -1,10,-1,5
set color "white"
plot text, at 2,-.8: "Ratio of Forcing Freq/Natural Freq. "
plot 0,0;0,5
plot 0,0;10,0
for i=1 to 10
plot i,-.2;i,0
plot text, at i,-.6: str$(i)
next i
for i=1 to 10
plot -.2,i;0,i
plot text, at -.6,i: str$(i)
next i
for numper=.25 to 1.5 step .25
if numper=.25 then let fend=1
if numper=.5 then let fend=0
if numper=.75 then let fend=-1
if numper=1 then let fend=0
if numper=.25 then let fend=1
if numper=1.5 then let fend=0
set color numper*4+1
!for freq=.1 to 10 step .1
let freq=1
for ffreq=.1 to 10 step .1
let fper=1/ffreq
let fpulse=numper*fper
let per=1/freq
let dt=per/2000
let ts=dt^2
let k=freq^2*4*pi^2
let dstat=1/k
let xo=dstat
let x=dstat
let xo=0
let x=0
let w=ffreq*2*pi
for t=0 to 10*per step dt
if t<fpulse then let f=sin(w*t) else let f=fend    ! This was let f=0
let ftot=f-k*x
let Xnew=2*X-XO+ftot*ts
let xo=x
let x=xnew
if abs(x)>xmax then let xmax=abs(x)
let amp=xmax/dstat
next t
```

```
plot ffreq/freq,amp;
let xmax=0
let xmin=0
next ffreq
plot ffreq/freq,amp
!next freq
plot text, at 3.5,2.5+numper: str$(numper)
next numper

set color "black"
plot 0,0;10,0
plot 0,0;0,10
for i=0 to 5
plot  -.1,i;0,i
plot text, at -.2,i: str$(i)
next i
for i=0 to 10
plot i,-.1;i,0
plot text, at i,-.2: str$(i)
next i
plot text, at 3.5,2.5+numper: "Number of Forcing Function Periods"
plot text, at 4.25,4.75: "Amplification vs. Frequency Ratio"
end
```

Appendix C
Email From Checker Regarding Proper Damping Modeling

From Han Zhang

Actually I don't mean which number is better, 5% or 10%. I just mean that it is better for the document to be consistent with the model, so that others can understand the document.

From your result of 1% and 10%, there isn't much difference in the DLF, and from the freq difference (60Hz excitation and 243Hz first freq and only quarter period loading), I think this result is reasonable.
Han.
On Wed, Mar 28, 2018 at 2:13 PM, Peter Titus <ptitus@pppl.gov> wrote:

Damping

CAE ASSOCIATES

- Rayleigh damping constants α and β
  - Used as multipliers of [M] and [K] to calculate [C]:

    $[C] = \alpha[M] + \beta[K]$
    $\alpha/2\omega + \beta\omega/2 = \xi$

    - Where ω is the frequency, and ξ is the damping ratio.

```
Frequency=1600
bdamp=2*percentdamp/(Frequency*2*3.1416)
betad,bdamp       !Damping
adamp= 2*percentdamp*frequency*2*3.1416
alphd,adamp       !Damping
```

Bdamp=2*percentdamp/ω_1

adamp=2*percentdamp*ω_1

ξ=adamp/(2*ω_1)+bdamp*ω_1/2= percentdamp+percentdamp=2* percentdamp

if you use percentdamp=0.05, ξ=0.1.