Clusering results around peaks for full-harmonic analyses in ANSYS

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Abstract

This article presents a method for obtaining full harmonic solutions clustered around potential peak responses. Full harmonic analyses provide exact solutions, typically calculated at equally spaced intervals over the desired frequency range. Mode-superposition analyses, however, provide approximate solutions, but can be clustered around potential resonant peaks. The hybrid method discussed in this article uses a modal solution to determine natural frequencies, which are then used to calculate clusters of points surrounding those frequencies. Full harmonic solutions can then be performed at these clustered points. Examples and input files are provided in order to utilize this method.

Keywords: Harmonic Response, Full Harmonic, Mode Superposition, Clustering
Tested in: ANSYS 11.0 SP1

1 Introduction

When analyzing the harmonic response of a structural system in ANSYS 11.0, users have the option of choosing among three solution methods, namely full, reduced, and mode superposition. In ANSYS Workbench Simulation 11.0, the reduced method is not available, but this method is less-commonly used than the other two. Each of these methods has benefits and drawbacks, so features of one may not be available to the other, potentially making the choice difficult.

The full method has the benefit of providing an exact solution at each solution point and supports all types of loads including nonzero displacements; however, the solution points are generally calculated at equally-spaced intervals, possibly missing the extremes at resonant peaks. The mode-superposition method has the benefit of typically requiring less memory and computational time, and it can cluster results around peak responses; however, the solution is approximate, and it does not fully support nonzero displacements at ANSYS 11.0.

A hybrid method could combine the benefits of both methods, such that the solution is exact at each solution point, can be clustered around peaks, and can support all types of loads. This article provides a method for obtaining this type of solution.

2 Harmonic Response Analysis – Solution Methods

A harmonic response analysis assumes that the applied loads and the steady-state response vary sinusoidally (harmonically) with time. The time-dependent equations of motion are given by

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F^a\} \quad , \tag{1}$$

where M, C, and K are the structural mass, damping, and stiffness matrices, respectively; $\ddot{u}$, $\dot{u}$, and u are the nodal acceleration, velocity, and displacement vectors, respectively; and F^a is the applied load vector. All points in the structure are assumed to oscillate at the same frequency but not necessarily in phase, so the complex displacement vector may be defined as

$$\{u\} = \left\{u_{\max} e^{i\phi}\right\} e^{i\Omega t} \quad , \tag{2}$$

and similarly, the complex force vector as

$$\{F\} = \left\{F_{\max} e^{i\phi}\right\} e^{i\Omega t} \quad . \tag{3}$$

Substituting Equations 2 and 3 into Equation 1, then simplifying gives the complex equation of harmonic motion.

$$\Big([K] - \Omega^2 [M] + i\Omega [C]\Big)\Big(u_{\max} e^{i\phi}\Big) = \left\{F_{\max} e^{i\phi}\right\} \tag{4}$$

A full description of each of these terms as well as the equation development can be found in the ANSYS Theory Reference [1].

The reduced method (HROPT,REDUC) uses master degrees of freedom to condense the problem size, allowing for a less-expensive analysis in terms of solution time; this method is less common and will not be discussed here. The focus of this article will be on the full and mode-superposition methods.

The full solution method (HROPT,FULL) solves Equation 4 directly. This equation can be rewritten as

$$[K_c]\{u_c\} = \{F_c\} \quad , \tag{5}$$

where c denotes a complex matrix or vector. It can be seen that this system of equations resembles the form of those for a linear static analysis. In fact, the same solvers and solution methods used for linear statics can be adapted for complex arithmetic and used to solve the set of simultaneous equations in Equation 5. A frequency range is chosen over which to solve, and results at equally-spaced points within that range are calculated.

The mode-superposition method (HROPT,MSUP) requires that a modal analysis precedes the harmonic analysis, then uses the frequencies and mode shapes to characterize the dynamic response of the structure. Instead of solving in nodal coordinates, as in the full method, the MSUP method solves for a set of modal coordinates using

$$\left(-\Omega^2 + i2\omega_j\Omega\xi_j + \omega_j^2\right) y_{jc} = f_{jc} \quad , \tag{6}$$

where y_{jc} is the complex amplitude of the modal coordinate for mode j, Ω is the imposed circular frequency, ω_j is the natural circular frequency of mode j, ξ_i is the fraction of critical damping for mode j, and f_{jc} is the complex force amplitude. The modal coordinates, y_{jc} are used to calculate the individual mode contributions, which are then combined to calculate the complex displacements.

As Ogata [2] points out, a resonant peak occurs where the imposed frequency, Ω, matches the natural frequencies, ω_j, of the system. In the full method, the natural frequencies of the system were not needed to calculate the harmonic response, but in the MSUP method, these frequencies were calculated during the modal analysis. Consequently, the harmonic solution points can be calculated at and near these natural frequencies, since they are already known, to find the extreme peaks.

The hybrid method in this article first solves a modal analysis to obtain the natural frequencies of the system, then uses the clustering technique outlined in the Theory Reference [1], and finally uses the full solution method to solve at each solution point determined by the clustering algorithm.

3 Clustering Results using Frequency Spacing

ANSYS provides an automatic method of spacing harmonic frequency results (HROUT,,ON) such that the solution points are clustered around resonant peaks.

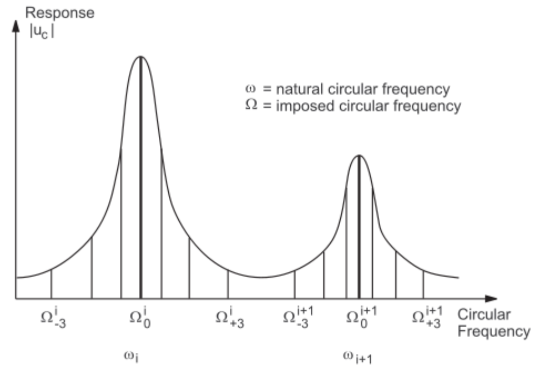

Figure 1: Frequency spacing (souce: Theory Reference for ANSYS and ANSYS Workbench [1]).

Essentially, the frequency-spacing algorithm uses the modal damping ratio to find points close to the resonant frequency, as shown in Figure 1. The algorithm used for calculating the solution points is outlined in the Theory Reference [1] and will not be repeated here.

4 Modal Analysis – Mode Extraction Methods

A modal analysis is used to obtain the natural frequencies of the system. There are several methods at ANSYS 11.0 used to find these frequencies, such as Block Lanczos, PCG Lanczos, subspace, reduced (Householder), unsymmetric, damped, and QR damped. Each method has benefits and drawbacks, but the Block Lanczos method is a fast and powerful method for small- to medium-sized models, even for a large number of modes—the related PCG Lanczos method is best for large models and a small number of modes. While the details of each method will not be discussed here, a short discussion on damping may be valuable.

The Structural Analysis Guide [3] notes that damping is present in most systems and suggests that it should be included in a dynamic analysis. In addition, Ogata [2] shows that both the frequency and magnitude of a resonant peak depends on the damping value. Consequently, the mode extraction method used here should be one that includes damping, such as the damped (MODOPT,DAMP) or QR damped (MODOPT,QRDAMP) method. The effective damping ratio is, in fact, required for the clustering algorithm described in the Theory Reference [1], and it can be retrieved using the *GET command [4]

(`*GET,Par,MODE,N,DAMP`). Although damping is not included in the Block Lanzos (`MODOPT,LANB`) extraction method, the damping values are populated and retrievable using the `*GET` command if defined; however, these values are not fully populated at ANSYS 11.0 for the damped and QR damped methods. As a result, this article will focus only on the Block Lanzos method, leaving the damped and QR damped methods for a future work.

5 Finite Element Test Model

An example model used by Imaoka [5], shown in Figure 2, provides a convenient starting point for the present article.

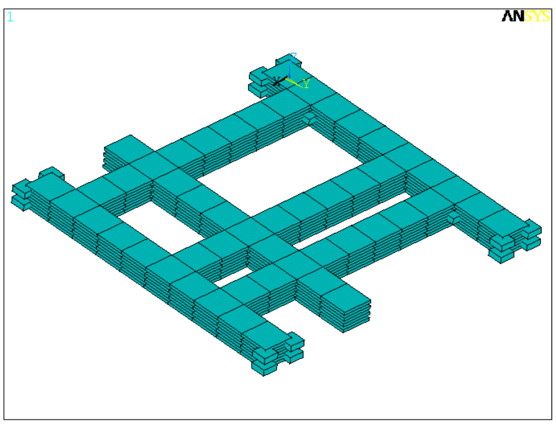

Figure 2: Finite element model presented by Imaoka (souce: STI0803 [5]).

This fictitious model, consisting of layers of shell elements connected together by beam elements, is excited at two nodes in addition to a pressure load on the top plate (input available in Appendix B.1). The harmonic response is then calculated using the full method with no clustering (Appendix B.2), the mode-superposition method with clustering (Appendix B.3), and finally the hybrid method (Appendix B.4). The acceleration response is plotted as an example result for all cases (Appendix B.5).

6 Results and Discussion

The harmonic response of the FE test model obtained using the full method with no clustering can be seen in Figure 3.

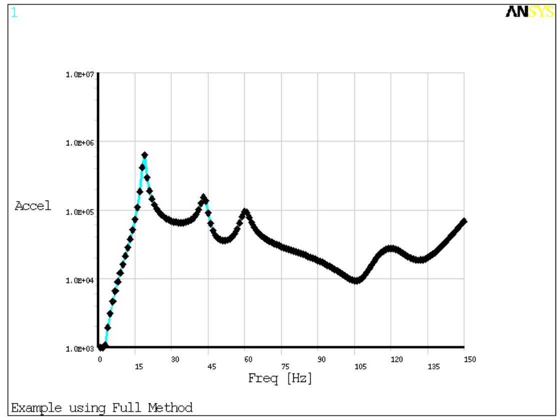

Figure 3: Acceleration response obtained with the full method and no clustering.

An excessive number of points were solved with this method to highlight the following points:

- the apparent peaks shown in the graph may not be the extreme peaks, depending on the closeness of the equally-spaced points to the natural frequencies, and
- most of the resulting points lie between peaks, where the results are likely not of interest, making the solution computationally inefficient.

It is for these reasons that a clustering option can be useful.

The results from the FE test model obtained using the mode-superposition method with clustering can be seen in Figure 4.

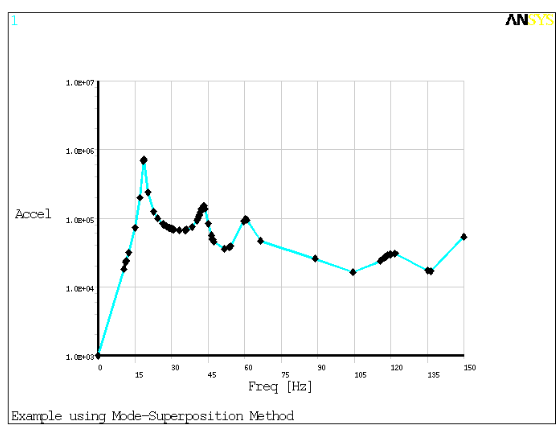

Figure 4: Acceleration response obtained with the mode-superposition method and clustering option.

It can be seen here that there are relatively-wide bands of frequency, approaching 15% in one case, in which there are no solution points. While this makes the response graph look somewhat jagged, these spaces are between resonant peaks by design of the clustering algorithm, as the results in these bands are often not of interest. The modal coordinates output key was set in this analysis (`HROPT,,,,YES` which writes the `jobname.MCF` file) so that the clustered frequencies could be compared to those calculated in the hybrid method.

The results from the FE test model using the hybrid method presented in the present article are shown in Figure 5.

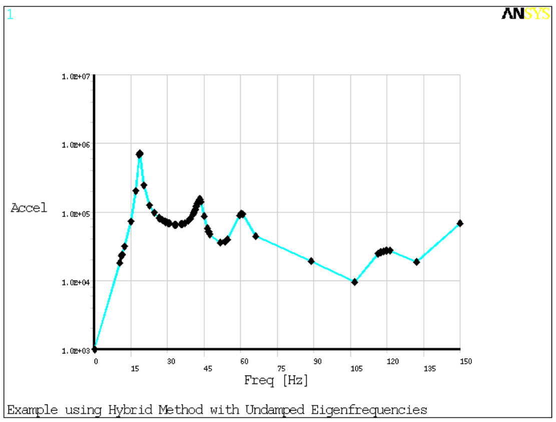

Figure 5: Acceleration response obtained with the hybrid method and clustering option.

This curve looks much like that from the mode-superposition method with the clustering option, but each point is an exact solution according to the full solution method. Appendix A contains a table comparing the natural frequencies resulting from the modal analysis to the clustered frequencies from the MSUP and hybrid methods.

7 ANSYS Workbench

The method described in this article to obtain clustered results for a full-harmonic analysis can easily be used in the ANSYS Workbench environment. The user must have one modal branch and one harmonic-response branch (the latter using the full solution method) in the model. First, the damping values are needed for the calculation of the clustered frequencies, so a short command object containing the desired damping values must be added before the solution of the modal analysis (see Appendix B.6). Next, the clustered frequencies are calculated using a command object in the postprocessing stage of the modal analysis (see Appendix B.7) and stored in a text file in the parent directory. A final command object in the harmonic branch loops through the calculated frequencies, solving for each point that was stored in the text file (see Appendix B.8). The results can be postprocessed as usual, as shown in Figure 6 (note that the model used in Workbench was not the same as that used earlier in this article).

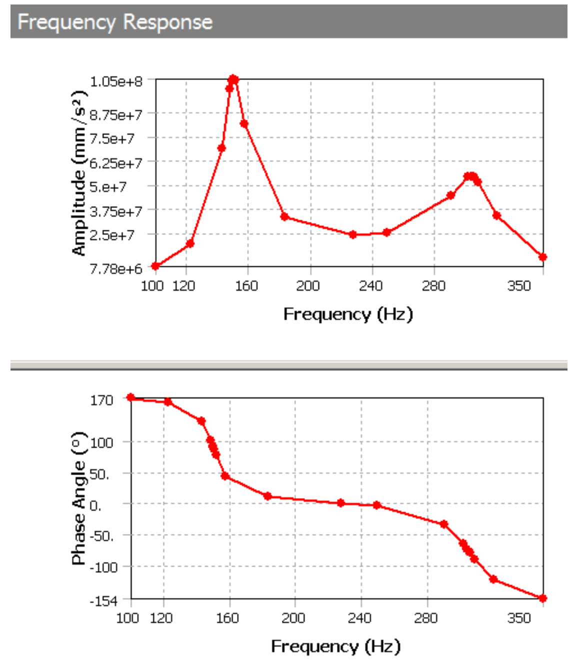

Figure 6: Acceleration response obtained with the hybrid method in ANSYS Workbench.

8 Conclusions

A full harmonic solution with clustering was be achieved by first running a modal soltuion to deternine natural frequencies and then by clustering full harmonic solutions around the potential peaks. The method discussed here combined some of the benefits of a mode-superposition harmonic with those of a full harmonic.

References

[1] ANSYS, Inc., "Theory Reference for ANSYS and ANSYS Workbench: ANSYS Release 11.0," 2007.

[2] K. Ogata, *Modern Control Engineering*, ch. 8: Frequency-Response Analysis. Prentice Hall, 4th ed., 2002.

[3] ANSYS, Inc., "Structural Analysis Guide: ANSYS Release 11.0," 2007.

[4] ANSYS, Inc., "Commands Reference: ANSYS Release 11.0," 2007.

[5] S. Imaoka, "Introduction to the residual vector method (STI0803)," 2008.

A Comparison of natural frequencies with harmonic frequencies

Table 1: Natural frequencies from modal analysis as compared to clustered frequencies in MSUP and hybrid harmonic methods.

Modal	MSUP	Hybrid		Modal	MSUP	Hybrid
	0.0000000	0.1135638				37.2350799
	10.4209800	10.4209789			38.3729300	38.3729321
	11.2656100	11.2656128				39.3646718
	11.3481700	11.3481740			40.4295600	40.4583977
11.3563812	11.3563800	11.3563812			40.7957200	40.8000560
	11.3563800	11.3563812		40.8369879	40.8369900	40.8369879
	11.3563800	11.3563813			40.8783000	40.8739532
	11.3563800	11.3563813			41.2485200	41.2191207
11.3563813	11.3563800	11.3563813			41.3562100	41.3562106
	11.3563800	11.3563813			41.4546400	41.4872150
	11.3563800	11.3563813			41.8326500	41.8375621
	11.3645900	11.3645945		41.8754333	41.8754300	41.8754333
	11.4478800	11.4478811			41.9182600	41.9133388
	12.3757500	12.3757467			42.3004900	42.2672844
	15.0172900	15.0172852			42.6471900	42.6471871
	17.0974200	17.1397041			42.9780000	43.0004657
	18.5198800	18.5288995			43.3738700	43.3772963
	18.6634400	18.6646904		43.4189408	43.4189400	43.4189408
18.6781890	18.6781900	18.6781890			43.4219300	43.4219334
	18.6929500	18.6916975		43.4249259	43.4249300	43.4249259
	18.8378500	18.8286815			43.4700600	43.4666164
	20.4051100	20.3547706			43.8704700	43.8475338
	22.6928800	22.6928821			45.1341400	45.1341388
	24.3822900	24.5077259			46.3564900	46.3760021
	26.4668600	26.4941090			46.7929900	46.7960112
	26.6844300	26.6882738		46.8433516	46.8433500	46.8433516
26.7075752	26.7075800	26.7075752			46.8937700	46.8907398
	26.7307400	26.7268907			47.3353200	47.3154107
	26.9504800	26.7314752			51.6439400	51.5457797
		26.9227614			53.5123200	53.5123191
	27.9192500	27.9192534			54.3613400	54.6729794
		28.8980961			59.4993100	59.5765502
	28.8636000	29.1048863			60.1075300	60.1198038
	29.1049900	29.1098788		60.1812867	60.1812900	60.1812867
29.1309316	29.1309300	29.1309316			60.2551400	60.2428324
	29.1569000	29.1519996			60.8710800	60.7921616
	29.4007300	29.3656430			66.6243100	66.2445563
	29.8247200	29.8247191			88.8670000	88.8669989
	30.2355800	30.2745806			104.4218000	106.7409550
	30.4909100	30.4964509			115.7228000	116.3589160
30.5185065	30.5185100	30.5185065			117.3194000	117.4306780
	30.5186800	30.5186768		117.5527112	117.5527000	117.5527110
30.5188471	30.5188500	30.5188471			117.7865000	117.6748710
	30.5464700	30.5429674				118.5980540
	30.8044300	30.7797297			118.6838000	118.6837920
		32.7818928				118.7587550
	33.2135400	33.2135415			119.5731000	119.6904830
		33.3405194		119.8148723	119.8149000	119.8148720
	35.5621500	35.5845922			120.0572000	119.9393910
	35.8738000	35.8771169			121.7309000	121.0441750
35.9082359	35.9082400	35.9082359			134.9663000	131.9511320
	35.9085600	35.9085561			136.3038000	150.0000000
35.9088763	35.9088800	35.9088763			149.9955000	
	35.9433500	35.9408830			149.9998000	
	36.2583400	36.2414549				

B ANSYS Input Files

All input files used for the examples presented in this article are included in the following sections. Header information and page numbering has been removed to simplify copy-and-paste operations.

B.1 Preprocessing file for all harmonic-response examples

```
my_freqbeg = 0
my_freqend = 150
my_freqnum = 100
my_factor  = 2
my_steps   = my_freqend-my_freqbeg

/PREP7
ET,1,63
ET,2,4
R,1,.1
R,2,.5**2,.5**4/12,.5**4/12,.5,.5
MP,EX  ,1,10E6
MP,NUXY,1,0.3
MP,DENS,1,0.1/386.1
MP,EX  ,2,30E6
MP,NUXY,2,0.3
MP,DENS,2,0.28/386.1

RECTNG,,1,,10
RECTNG,6,7,,10
RECTNG,9,10,,10
RECTNG,,10,1,2
RECTNG,,10,5,6
RECTNG,,10,7,8
AOVLAP,ALL

ESIZE,1
MSHKEY,1
AMESH,ALL

AGEN,4,ALL,,,0,0,0.2

TYPE,2$REAL,2$MAT,2

E,NODE( 0, 0,0),NODE( 0, 0,0.2)
E,NODE( 1, 0,0),NODE( 1, 0,0.2)
E,NODE( 9, 0,0),NODE( 9, 0,0.2)
E,NODE(10, 0,0),NODE(10, 0,0.2)
E,NODE( 0,10,0),NODE( 0,10,0.2)
E,NODE( 1,10,0),NODE( 1,10,0.2)
E,NODE( 9,10,0),NODE( 9,10,0.2)
E,NODE(10,10,0),NODE(10,10,0.2)

E,NODE( 1, 8,0.2),NODE( 1, 8,0.4)
E,NODE( 9, 8,0.2),NODE( 9, 8,0.4)
E,NODE( 9, 2,0.2),NODE( 9, 2,0.4)
E,NODE( 9, 5,0.2),NODE( 9, 5,0.4)
E,NODE( 1, 5,0.2),NODE( 1, 5,0.4)
E,NODE( 1, 2,0.2),NODE( 1, 2,0.4)

E,NODE( 0, 0,0.4),NODE( 0, 0,0.6)
E,NODE( 1, 0,0.4),NODE( 1, 0,0.6)
E,NODE( 9, 0,0.4),NODE( 9, 0,0.6)
E,NODE(10, 0,0.4),NODE(10, 0,0.6)
E,NODE( 0,10,0.4),NODE( 0,10,0.6)
E,NODE( 1,10,0.4),NODE( 1,10,0.6)
E,NODE( 9,10,0.4),NODE( 9,10,0.6)
E,NODE(10,10,0.4),NODE(10,10,0.6)

LSEL,S,LOC,Y,0
LSEL,A,LOC,Y,10
LSEL,R,LOC,X,6,7
LSEL,R,LOC,Z,0
NSLL,S,1
```

```
D,ALL,ALL

ASEL,S,LOC,Z,0.6
ALLSEL,BELOW,AREA
CM,e_pres,ELEM

NSEL,ALL
NSEL,S,NODE,,NODE(1,6,0.2)
n_force1=NDNEXT(0)
CM,n_force1,NODE

NSEL,ALL
NSEL,S,NODE,,NODE(9,6,0.4)
n_force2=NDNEXT(0)
CM,n_force2,NODE

ALLSEL

DMPRAT,0.025
BETAD,0.025/(ACOS(-1)*my_freqend)

FINISH
```

B.2 Full harmonic solution with no clustering

```
FINISH
/CLEAR

/TITLE,Example using Full Method

/INP,example1prep,inp

/SOLU
ANTYPE,HARMIC
HROPT,FULL
HARFRQ,my_freqbeg,my_freqend
NSUBST,my_steps
KBC,1

F,n_force1,FZ,0,-75
F,n_force2,FZ,100,100
SFE,e_pres,1,PRES,,0.5

SOLVE
FINISH

/INP,example1post,inp
```

B.3 Mode-superposition solution with clustering

```
FINISH
/CLEAR

/TITLE,Example using Mode-Superposition Method

/INP,example1prep,inp

NN = 4

/SOLU
ANTYPE,MODAL
MODOPT,LANB,my_freqnum,0,my_freqend*my_factor
MXPAND,my_freqnum,,,YES

SFE,e_pres,1,PRES,,0.5
F,n_force1,FZ,0,-75
F,n_force2,FZ,100,100

SOLVE
```

```
FDELE,ALL,ALL
SFEDELE,ALL,ALL,ALL
FINISH

/SOLU
ANTYPE,HARMIC
HROPT,MSUP,,,YES
HROUT,,ON
HARFRQ,my_freqbeg,my_freqend
NSUBST,NN
KBC,1

LVSCALE,1

SOLVE
FINISH

/SOLU
EXPASS,ON
NUMEXP,ALL,,,YES
SOLVE
FINISH

/INP,example1post,inp
```

B.4 Full harmonic solution with clustering (hybrid method)

```
FINISH
/CLEAR

/TITLE,Example using Hybrid Method with Undamped Eigenfrequencies

/INP,example1prep,inp

NN = 4

/SOLU
ANTYPE,MODAL
MODOPT,LANB,my_freqnum,my_freqbeg,my_freqend
SOLVE
FINISH

/POST1
! define an array to hold the frequencies
*GET,nummode,ACTIVE,0,SET,NSET
! add an additional point for the starting and ending frequency
*DIM,all_frequencies,ARRAY,nummode+2

! since a harmonic analysis will not solve with a frequency of zero,
! a small factor of the lowest frequency will be used in place
*IF,my_freqbeg,EQ,0,THEN
  *GET,freq,MODE,1,FREQ
  all_frequencies(1) = freq/100
*ELSE
  all_frequencies(1) = freqbeg
*ENDIF

! fill the array with frequencies resulting from the modal analysis
*DO,ii,1,nummode
  *GET,freq,MODE,ii,FREQ
  all_frequencies(ii+1) = freq
*ENDDO

! add the ending frequency
all_frequencies(nummode+2) = my_freqend

! since there is no point of solving for the same frequency more than once,
! duplicates will be set to zero and removed in subsequent operation
*DO,ii,2,nummode+2
  *IF,all_frequencies(ii),EQ,all_frequencies(ii-1),THEN
    all_frequencies(ii) = 0
  *ENDIF
```

```
*ENDDO

! zero-entries are removed from the array
*VMASK,all_frequencies
*VFUN,frequencies,COMP,all_frequencies
*SET,all_frequencies
*VSCFUN,nummode,NUM,frequencies

! calculate the upper-bound for the number of solution points
numpts = 2*NN*(nummode-2)+1

! define an array to hold all solution points for the harmonic analysis
*DIM,points,ARRAY,numpts

! the lowest frequency can simply be copied over
points(1) = frequencies(1)

! this approximates the clustering algorithm from Theory Manual section 17.4.7
count = 2
*DO,ii,2,nummode-1
  ! get the frequency that will be clustered around
  omega = frequencies(ii)
  ! get the damping
  *GET,xi,MODE,ii-1,DAMP

  ! start with the low side, and calculate the points according to the algorithm
  *DO,jj,NN-1,1,-1
    bb = 2*(NN-jj)/(NN-1)
    aa = 1+xi**bb
    ! if the calculated frequency is lower than the adjacent frequency
    ! on the low side, then don't include it
    *IF,omega/aa,GT,frequencies(ii-1),THEN
      points(count) = omega/aa
    *ENDIF
    count = count+1
  *ENDDO

  ! then include the point directly at the frequency
  points(count) = omega
  count = count+1

  ! then move to the high side
  *DO,jj,1,NN-1
    bb = 2*(NN-jj)/(NN-1)
    aa = 1+xi**bb
    ! if the calculated frequency is higher than the adjacent frequency
    ! on the high side, then don't include it
    *IF,omega*aa,LT,frequencies(ii+1),THEN
      points(count) = omega*aa
    *ENDIF
    count = count+1
  *ENDDO

  ! then, add the points in between the frequencies
  *IF,ii,LT,nummode,THEN
    points(count) = (frequencies(ii)+frequencies(ii+1))/2
  *ENDIF
  count = count+1
*ENDDO

! and finally, the highest frequency can simply be copied over
points(count-1) = my_freqend

! since there was logic to remove some points, there still could be some
! zeros present, so they are simply removed
*VMASK,points
*VFUN,soln_points,COMP,points
*SET,points

! since there is also a chance that the calculated points could overlap,
! the array is sorted to ensure ascending order
*VFUN,soln_points,ASORT,soln_points

! print the array to the output file for tracking purposes
```

```
*STAT,soln_points(1)

/SOLU
ANTYPE,HARM
HROPT,FULL
KBC,1
F,n_force1,FZ,0,-75
F,n_force2,FZ,100,100
SFE,e_pres,1,PRES,,0.5
NSUBST,1
*VSCFUN,numsoln,NUM,soln_points
*DO,ii,1,numsoln
  HARFRQ,soln_points(ii)
  SOLVE
*ENDDO
FINISH

/inp,example1post,inp
```

B.5 Postprocessing file for all harmonic-response examples

```
/POST26
/PLOP,INFO,2
/GROP,LOGY,ON
/XRANGE,my_freqbeg,my_freqend
/YRANGE,1E3,1E7
/GMARKER,1,3
/AXLAB,X,Freq [Hz]
/AXLAB,Y,Accel

NSOL,2,n_force1,U,Z
PROD,2, 1, 1, 2,,,,-2*ACOS(-1),2*ACOS(-1),1
PLVAR,2
FINISH
```

B.6 Workbench command object to set damping

```
DMPRAT,ARG1
BETAD, ARG2
```

B.7 Workbench command object to calculate clustered frequencies

```
freqbeg = ARG1    ! starting frequency
freqend = ARG2    ! ending frequency
NN      = ARG3    ! cluster number

! use variables to store filename
filenam = '../soln_points'
fileext = 'txt'

! define an array to hold the frequencies
*GET,nummode,ACTIVE,0,SET,NSET
! add an additional point for the starting and ending frequency
*DIM,all_frequencies,ARRAY,nummode+2

! since a harmonic analysis will not solve with a frequency of zero,
! a small factor of the lowest frequency will be used in place
*IF,freqbeg,EQ,0,THEN
  *GET,freq,MODE,1,FREQ
  all_frequencies(1) = freq/100
*ELSE
  all_frequencies(1) = freqbeg
*ENDIF

! fill the array with frequencies resulting from the modal analysis
*DO,ii,1,nummode
  *GET,freq,MODE,ii,FREQ
  all_frequencies(ii+1) = freq
*ENDDO
```

```
! add the ending frequency
all_frequencies(nummode+2) = freqend

! since there is no point of solving for the same frequency more than once,
! duplicates will be set to zero and removed in subsequent operation
*DO,ii,2,nummode+2
  *IF,all_frequencies(ii),EQ,all_frequencies(ii-1),THEN
    all_frequencies(ii) = 0
  *ENDIF
*ENDDO

! zero-entries are removed from the array
*VMASK,all_frequencies
*VFUN,frequencies,COMP,all_frequencies
*SET,all_frequencies
*VSCFUN,nummode,NUM,frequencies

! calculate the upper-bound for the number of solution points
numpts = 2*NN*(nummode-2)+1

! define an array to hold all solution points for the harmonic analysis
*DIM,points,ARRAY,numpts

! the lowest frequency can simply be copied over
points(1) = frequencies(1)

! this approximates the clustering algorithm from Theory Manual section 17.4.7
count = 2
*DO,ii,2,nummode-1
  ! get the frequency that will be clustered around
  omega = frequencies(ii)
  ! get the damping
  *GET,xi,MODE,ii-1,DAMP

  ! start with the low side, and calculate the points according to the algorithm
  *DO,jj,NN-1,1,-1
    bb = 2*(NN-jj)/(NN-1)
    aa = 1+xi**bb
    ! if the calculated frequency is lower than the adjacent frequency
    ! on the low side, then don’t include it
    *IF,omega/aa,GT,frequencies(ii-1),THEN
      points(count) = omega/aa
    *ENDIF
    count = count+1
  *ENDDO

  ! then include the point directly at the frequency
  points(count) = omega
  count = count+1

  ! then move to the high side
  *DO,jj,1,NN-1
    bb = 2*(NN-jj)/(NN-1)
    aa = 1+xi**bb
    ! if the calculated frequency is higher than the adjacent frequency
    ! on the high side, then don’t include it
    *IF,omega*aa,LT,frequencies(ii+1),THEN
      points(count) = omega*aa
    *ENDIF
    count = count+1
  *ENDDO

  ! then, add the points in between the frequencies
  *IF,ii,LT,nummode,THEN
    points(count) = (frequencies(ii)+frequencies(ii+1))/2
  *ENDIF
  count = count+1
*ENDDO

! and finally, the highest frequency can simply be copied over
points(count-1) = freqend

! since there was logic to remove some points, there still could be some
```

```
! zeros present, so they are simply removed
*VMASK,points
*VFUN,soln_points,COMP,points
*SET,points

! since there is also a chance that the calculated points could overlap,
! the array is sorted to ensure ascending order
*VFUN,soln_points,ASORT,soln_points

! print the array to the output file for tracking purposes
*STAT,soln_points(1)

! finally, write the array of solution points to a text file
*CFOPEN,%filenam%,%fileext%
*VWRITE,soln_points(1)
(E25.15)
*CFCLOS
```

B.8 Workbench command object to solve harmonic response

```
filenam = '../soln_points'
fileext = 'txt'

/INQUIRE,numsoln,LINES,%filenam%,%fileext%

*DIM,soln_points,ARRAY,numsoln
*VREAD,soln_points(1),%filenam%,%fileext%,,,numsoln
(E25.15)

NSUBST,1
*DO,ii,1,numsoln
  HARFRQ,soln_points(ii)
  SOLVE
*ENDDO

! prevent Simulation from issuing an additional "solve"
*ABBR,SOLVE,NOSOLVE
```