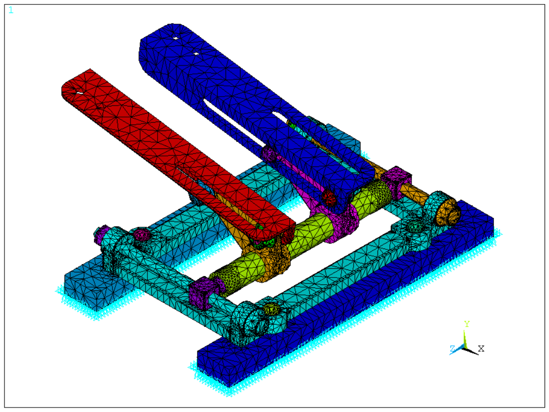
Date	June 13, 2004	Memo Number	STI:04/03E
Subject	**Sheldon's ANSYS Tips and Tricks: PSD Calculation Efficiency**		
Keywords	PSD, Random Vibration, SPRS		

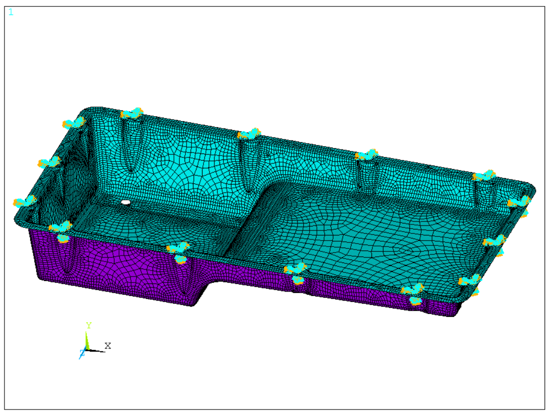
1. Introduction:

PSD (Power Spectral Density) analysis, or more commonly known as Random Vibration analysis, is a statistical dynamic analysis dealing with the effects of a random excitation. The excitation can be a base (displacement, velocity, acceleration) or nodal (force, pressure) excitation and is assumed to be a stationary random process with zero mean value. The details of performing PSD analyses in ANSYS are outside of the scope of this memo but are given in Chapter 6 of the *Structural Analysis Guide* as well as Section 17.7 of the *ANSYS Theory Reference*.

A very common use of PSD analyses is to look at the response of a system under a single base excitation, such as the case with many aerospace and civil applications. The default PSD settings are very general in nature and may consequently be inefficient for such a situation. This memo hopes to outline some ways in which the user may obtain more efficient PSD solutions for the specific instance of single base excitation with relatively flat spectrum (although some techniques may be extrapolated for other cases).[1]

2. Background Discussion:





For illustrative purposes, two models, shown on the right, were chosen to demonstrate some features discussed herein.

The first model is a sample SolidWorks assembly comprised of SOLID92 elements with TARGE170 & CONTA174 contact elements, with the base excitation specified on the bottommost areas. This model will simply be referred to as "support."

The second model is a sample Inventor part, which is made of SHELL181 elements. The excitation is specified on fourteen holes around the perimeter of the model, and this part will be referred to as "oilpan1".

A PSD analysis consists of performing a modal analysis first because the mode superposition method (i.e., generalized coordinates) is the basis for random vibration analyses. For this example, about 140 modes were requested for "support" and 200 modes for "oilpan1." Stress results were calculated with the MXPAND command, necessary for subsequent PSD stress evaluation.

After the modal analysis, a PSD analysis was executed. For both models, a white noise (0.1g) in the y-direction was specified, and 1-sigma displacement, velocity, and acceleration results were obtained.

The statistics for the runs are tabulated below[2]:

		Nodes	Elements	Modes	Scratch	CPU Time	Speed
support	modal	116704	68689	139	379 MB	23737 s	1.00
	psd	116704	68689		1641 MB	45560 s	1.92
oilpan1	modal	17385	17049	200	256 MB	12989 s	1.00
	psd	17385	17049		465 MB	23084 s	1.78

Because the number of requested modes is very high, the modal analysis takes a while to run on this particular hardware. The PSD runs take nearly twice as much total CPU time and much more scratch memory as the modal analysis for these two cases.

[1] Present discussion taken from author's previous memo "STI72:001020 – PSD Tips and Tricks" but updated for 8.1

[2] CPU time is shown rather than wall time, but, for hardware with fast disk I/O, the CPU time should be a large portion of wall time.

3. Efficient PSD Runs – Use of PSDCOM:

A PSD solution not only involves the initial modal analysis, but it also includes calculation of partipation factors, mode combination for 1-sigma values, and evaluation of stresses. During the PSD solution, the elapsed CPU time is printed occasionally in the Output File. One can easily determine from this output which portion of the PSD run takes the most significant amount of time.

In the present case, the "support" and "oilpan1" models include all modes with the default significance level. 1-sigma displacement, velocity, and acceleration results are requested, including stress output. Consequently, from the Output File, one would notice that the mode combination portion takes a large amount of the solution time.

During the mode combination, the covariance terms are calculated and used in the mode combination.[3] If output printout is requested (OUTPR), one may view these terms in the Output File. Acceleration calculations

```
 *** ACCELERATION-TYPE QUANTITY ***

MAXIMUM TERM = 0.50184E+06

MODE  MODE   COVARIANCE     COVARIANCE
 I     J        TERM           RATIO

 1     1     0.43056E+06    0.85795
 2     1     0.16904E-06    0.33685E-12
 2     2     0.11721E-17    0.23356E-23
 3     1     -99595.        0.19846
 3     2    -0.15717E-06    0.31319E-12
 3     3     0.50184E+06     1.0000
 4     1    -0.10566E-07    0.21054E-13
 4     2    -0.78336E-20    0.15610E-25
 4     3     0.42943E-08    0.85569E-14
```

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
Mode 1	8.6E-01	3.4E-13	2.0E-01	2.1E-14	1.4E-02	3.6E-14
Mode 2		2.3E-24	3.1E-13	1.6E-26	7.3E-15	1.8E-26
Mode 3			1.0E+00	8.6E-15	3.0E-03	6.5E-15
Mode 4				4.6E-25	3.6E-13	9.8E-25
Mode 5					8.3E-01	2.4E-12
Mode 6						7.0E-24

for a simple case using 6 modes are shown below:
The table on the right is a matrix representation of the covariance ratios.

If the mode combination portion of the PSD analysis is the majority of the computational time, the use of the PSDCOM command may help in reducing the calculations. The PSDCOM command allows users to specify the *significance ratio (a.k.a. covariance ratio)* and/or the number of first few modes to use in the combination procedure. For example, the default significance level is 1e-4, so the following table shows the *included* terms in blue italics. Conversely, if the number of modes is set to the first 4, the included terms are shown with a light green background. (The use of both the significance ratio of 1e-3 and the first 4 modes will result in terms with blue italics and green background.)[4]

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
Mode 1	*8.6E-01*	3.4E-13	*2.0E-01*	2.1E-14	*1.4E-02*	3.6E-14
Mode 2		2.3E-24	3.1E-13	1.6E-26	7.3E-15	1.8E-26
Mode 3			*1.0E+00*	8.6E-15	*3.0E-03*	6.5E-15
Mode 4				4.6E-25	3.6E-13	9.8E-25
Mode 5					*8.3E-01*	2.4E-12
Mode 6						7.0E-24

If specified appropriately, the reduction of the number of modes used should not affect accuracy of 1-sigma results in any noticeable manner. However, one can always verify whether or not the smaller set of modes used is acceptable by comparing the 1-sigma/RMS result with the response PSD.

```
!Sample APDL comparing UZ at NODE
!/POST1 command for a node
*get,PARM1,node,NODE,u,z

!/POST26 command for the same node
store,psd
nsol,2,NODE,u,z
rpsd,3,2,,1,2
int1,4,3,1
extrem,4
*get,PARM2,vari,4,extrem,vmax
PARM2=sqrt(PARM2)

! PARM1 and PARM2 should match closely
```

The PSDCOM command only affects the 1-sigma results (load steps 3, 4, and/or 5) in /POST1. The mode combination calculation procedure is done via closed-form integration. On the other hand, the RPSD command in /POST26 is a numerical integration procedure performed on all modes in the result file, so it is independent of the PSDCOM command. By taking the square root of the integral (INT1) of the RPSD response at a node of interest, this scalar result can be compared with the 1-sigma (same as RMS) result in /POST1. The results should be similar if enough modes are used in the mode combination phase.

[3] The author assumes that the user is familiar with the mode combination procedure employed in ANSYS. If not, the user may refer to Section 17.7.12 of the *ANSYS Theory Reference*

[4] There is another way of specifying modal coupling terms via an undocumented option using "Frequency Ratio" input for SPOPT. This will be discussed in Appendix A.

In some cases, the user may wish to evaluate the covariance terms and ratios prior to specifying the selection of modes for the mode combination procedure. The PSDCOM command (load steps 3-5) may be included with the PFACT command (load step 2) to perform the PSD analysis in one step, or it may be included in a separate step after PFACT. If PSDCOM is run as a separate step, the user can review all Q_{ij} matrix terms in the Output File before deciding on the appropriate *significance level* and *number of modes* to use with PSDCOM.

For the examples used in this memo, the following table shows a comparison using different significance levels (i.e., covariance ratios) for PSDCOM and its effect on solution CPU time for a coarser mesh of the "support" model, considering 77 total modes:

		Nodes	Elements	Significance	Modes	CPU Time	Total Time	UX	UY	UZ	SX	SY	SZ	SEQV
support	modal	28941	15801		77	2472 s	3246 s							
	psd	28941	15801	1.00E-04		3095 s	3318 s	7.74E-03	2.17E-02	1.69E-03	3272.28	2700.15	3625.80	10427.1
	psd	28941	15801	1.00E-03		1182 s	1360 s	7.74E-03	2.17E-02	1.73E-03	3269.03	2695.23	3709.73	10403.9
	psd	28941	15801	1.00E-02		534 s	638 s	7.73E-03	2.17E-02	3.07E-04	3249.21	2651.84	1996.86	10336.3
	psd	28941	15801	1.00E-01		311 s	356 s	7.73E-03	2.17E-02	3.07E-04	3249.21	2651.84	1996.86	10336.3

As is apparent from the above table, increasing the minimal covariance ratio (i.e., significance level) drastically decreases the solution times. Note, however, that this means that fewer modes are considered, so the 1-sigma results may start to get affected, as shown on the last three columns for RMS values of maximum SX, SY, and SZ. In this case, the excitation was in the y-direction, but if the significance level was reduced to 1e-2, the SZ max value would be underpredicted. The overall RMS value for SEQV is not as affected drastically, however (< 1%).

An analogous situation occurs by using the first *n* modes via the second argument of the PSDCOM command, as it is another means of limiting the number of modes used for mode combination.

4. Efficient PSD Runs – Controlling the result output with OUTRES:

```
! Sample APDL to only
! calculate and save
! specified results
! (disp and stresses)
outres,all,none
outres,nsol,all
outres,strs,all
```

The previous section discussed a way to speed up calculation time by limiting the number of modes saved in the result file. The user can also (a) limit the type of results and (b) specify the nodes or elements for which results will be calculated and stored in the results file via the OUTRES command. This can be done for any type of analysis, not just PSD. By storing results only for displacements and stresses, for example, the .rst file will be smaller, and there will be significant computational savings.

To illustrate this difference, a comparison was made using the "support" model. One run saved all result quantities, whereas a second run stored only displacements, stresses, nodal forces, and reaction forces for each mode. In the modal analysis, a savings of about 50% total time was achieved. In the PSD analysis for this same model, the total solution time when selectively requesting output results was 60% of the original solution time. This represents a drastic case if the solution time is dominated by disk I/O (writing large .rst file), although the CPU speedup was about 30%. The speedup is affected by how much output is calculated via OUTRES.

		OUTRES	CPU Time	Total Time
support	modal	ALL	23737 s	38414 s
	psd	ALL	45560 s	93306 s
support	modal	selective	18166 s	19984 s
	psd	selective	31784 s	39466 s

The output results can also be requested for specific nodes or elements. For example, the user may request results only on the exterior of the model by creating a component and using that component in the OUTRES command. Of course, this means that if the user may wish to postprocess results which were not requested and stored, a new solution must be performed to recalculate those quantities.

One additional point worth noting is that the user should not have a non-zero .page file when running the PSD mode combination phase; otherwise, performance may suffer drastically. Ensure that a sufficient database memory size is specified when launching ANSYS ("-db" option via command line method or "Customization tab: Database (MB)" in the Launcher).

5. Efficient PSD Runs – Utilizing SPRS-type of PSD:

It is interesting to note that there exists another PSD method in ANSYS. Instead of using SPOPT,PSD, the user can specify a Single-Point Response Spectrum (SPRS), then specify PSD via SVTYP,4. Although SPRS is usually a deterministic analysis, the SPRS type 4 analysis utilizes simplified PSD calculations which may be suitable for single PSD base excitations with relatively flat spectrum.[5]

	SPOPT,PSD	SPOPT,SPRS$SVTYP,4
Specify Different Excitation Nodes from Constrained Nodes	Yes (D,,UX/UY/UZ,1.0)	No (SED)
PSD specification	Various (PSDUNIT)	Acceleration only
Graph PSD curve	Yes (PSDGRAPH)	No (listing available)
Damping Specification	ALPHAD; BETAD; DMPRAT; MDAMP	BETAD; DMPRAT; MDAMP; MP,DAMP
Mode Combination Method	PSDCOM	CQC, SRSS (or others)
Cross-term Specification	Yes (COVAL, QDVAL)	No
Spatial Correlation	Yes (PSDSPL)	No
Wave Propagation Excitation	Yes (PSDWAV)	No
1-σ Results	Stored in .rst (LS 3-5)	Read in .mcom file
Displacement Output	Relative or Absolute (PSDRES)	Relative only
Velocity Output	Relative or Absolute (PSDRES)	Relative only
Acceleration Output	Relative or Absolute (PSDRES)	Relative only
Statistical SEQV Output	Yes (8.1)	Not Available
RPSD Output	Available (RPSD)	Not Available
Covariance calculations	Available (CVAL)	Not Available

The procedure for SVTYP,4 is the same as regular Response Spectrum analyses. The user cannot specify which of the constrained DOF are used in base excitation – all constrained DOF are assumed to be excited (usually suitable for base excitation problems). The PSD curve is input via FREQ and SV commands, and it must take the form of accleration^2/Hz rather than g^2/Hz. Lastly, mode combination is done via CQC or SRSS method. A comparison between the aforementioned PSD method as well as the alternative SPRS-type PSD method is outlined on the right

There are some drawbacks to the SPRS-type of PSD analysis. Only relative output is available, so absolute quantities cannot be specified with this method. Moreover, RPSD and CVAL are not available for use with this technique. Because of this, the applicability of such an approach may be limited, although if users are only interested in RMS relative displacements and stresses, it may be worthwhile to consider this method.

The mode combination method is determined by the user. Unlike regular PSD analyses, PSDCOM is not used. Instead, CQC or SRSS are some methods which can be employed. Also, the *significance threshold* which is used by CQC and SRSS is the ratio of mode coefficients, not the terms of the covariance matrix, as with PSDCOM.

The selection of SRSS and CQC depends on whether or not the user wishes to include coupling effects of modes – this is usually most significant for closely-spaced modes. SRSS treats each mode independently, so it is an efficient but less accurate method – it is analogous to taking the diagonal terms only from the Q_{ij} covariance matrix. The CQC method, on the other hand, accounts for interaction of closely-spaced modes, which is similar to accounting for off-diagonal terms in Q_{ij}.[6] In other words, the CQC method is more accurate but more computationally expensive than SRSS.

A comparison of the mode coefficients from SPRS-type of PSD analyses and the covariance terms from PSD analyses for a different, simpler model are shown in the table below:[7]

Mode	Frequency	Modal PF	SRSS PF	SRSS MC	CQC PF	CQC MC	PSD PF	PSD COV	sqrt(COV)
1	22 Hz	8.4738E-16	8.474E-16	1.639E-16	8.474E-16	1.639E-16	-9.656E-16	3.0845E-32	1.7563E-16
2	24 Hz	4.3864E-16	4.386E-16	7.726E-17	4.386E-16	7.726E-17	-1.47E-15	6.2333E-32	2.4967E-16
3	40 Hz	-3.567E-15	-3.567E-15	-3.303E-16	-3.567E-15	-3.303E-16	2.8416E-15	6.7928E-32	2.6063E-16
4	**46 Hz**	**0.93268**	0.9327	**0.07274**	0.9327	**0.07274**	-0.93268	0.0052094	**0.07217617**
5	95 Hz	-6.427E-15	-6.426E-15	-1.955E-16	-6.426E-15	-1.955E-16	6.9922E-15	4.4833E-32	2.1174E-16
6	122 Hz	2.7967E-15	2.797E-15	5.84E-17	2.797E-15	5.84E-17	-2.639E-15	3.0145E-33	5.4904E-17
7	**183 Hz**	**0.32442**	0.3244	**0.00368**	0.3244	**0.00368**	-0.32442	1.3156E-05	**0.00362712**
8	220 Hz	-3.635E-15	-3.635E-15	-2.514E-17	-3.635E-15	-2.514E-17	3.0948E-15	4.7004E-34	2.168E-17
9	**233 Hz**	**-0.25755**	-0.2576	**-0.001424**	-0.2576	**-0.001424**	0.25755	2.1471E-06	**0.0014653**
10	261 Hz	8.2356E-16	8.236E-16	2.936E-18	8.236E-16	2.936E-18	-1.239E-15	2.144E-35	4.6303E-18
11	360 Hz	1.4274E-14	1.427E-14	2.289E-17	1.427E-14	2.289E-17	-1.429E-14	1.3213E-34	1.1495E-17
12	**367 Hz**	**0.12454**	0.1245	**1.94E-04**	0.1245	**1.94E-04**	-0.12454	8.9832E-09	**9.478E-05**

Examination of the equations solved will indicate that the modal covariance from PSD is similar to the square of the mode coefficients from the SPRS analysis, and this is reinforced by the table above. The coefficients from the .mcom file generated by the CQC combination method for different modes (interaction between modes) are also found to be analogous to the Q_{ij} off-diagonal terms (though the terms are not shown here).

[5] Refer to Section 17.7.5 in the Theory Reference for details.
[6] Note that the 10% Grouping Method (GRP) is another way of accounting for closely-spaced modes.
[7] In this table, "PF" stands for "participation factors" calculated in the analysis, "MC" are "mode coefficients", and "COV" is the "modal covariance term". Only diagonal terms are displayed. A simpler model with fewer modes was chosen to make comparison simpler.

Instead of comparing each output result quantity, verifying this relationship between mode coefficients and modal covariance matrix terms is a simple way of determining whether the SPRS-type of PSD analysis may be a suitable approximation for a regular PSD analysis, after both cases are run. There may be some instances where the SPRS-type of PSD analysis may not be suitable, even for a single base excitation, so some care needs to be exercised when using this method.

Using the "oilpan1" and "support" models discussed in this memo, three cases were run to compare SRSS and CQC with PSDCOM using default values for the significance factors:

		Nodes	Elements	Modes		Scratch	CPU Time	Total Time	UX	UY	UZ	SX	SY	SZ	SEQV
support	modal	116704	68689	139		379 MB	23737 s	38414 s							
	psd	116704	68689		PSDCOM	1641 MB	45560 s	93306 s	8.33E-03	2.34E-02	1.80E-03	3349.06	4058.62	2670.35	10408.6
	sprs	116704	68689	12	SRSS	130 MB	902 s	969 s	8.33E-03	2.34E-02	2.05E-03	3781.11	4430.33	3105.65	10006.7
	sprs	116704	68689	12	CQC	130 MB	2298 s	2349 s	8.33E-03	2.34E-02	1.82E-03	3466.49	4164.33	2762.49	10013.2
support	modal	28941	15801	77		256 MB	2472 s	3246 s							
	psd	28941	15801		PSDCOM	255 MB	3095 s	3318 s	7.74E-03	2.17E-02	1.69E-03	3272.28	2700.15	3625.80	10427.1
	sprs	28941	15801	13	SRSS	33 MB	272 s	284 s	7.74E-03	2.17E-02	1.87E-03	3271.82	2697.93	4036.20	9870.0
	sprs	28941	15801	13	CQC	33 MB	730 s	737 s	7.74E-03	2.17E-02	1.70E-03	3273.37	2701.21	3696.96	9870.7
oilpan1	modal	17385	17049	200		256 MB	12989 s	13543 s							
	psd	17385	17049		PSDCOM	465 MB	23084 s	29295 s	9.20E-04	1.16E-02	8.16E-04	1827.74	1189.54	2040.10	1935.32
	sprs	17385	17049	49	SRSS	31 MB	522 s	530 s	9.36E-04	1.16E-02	7.76E-04	1606.73	1191.72	1662.24	1576.65
	sprs	17385	17049	49	CQC	31 MB	10495 s	11013 s	9.15E-04	1.16E-02	8.04E-04	1907.48	1188.05	2225.59	2109.01

Note that with PSDCOM and the default significance level of 1e-4, many modes are considered, so the scratch space required and computational time is excessive. Recall from discussions in Sections 3 and 4 that there are ways to reduce the amount of memory and CPU time for PSDCOM calculations.

That being said, however, the SPRS-type of PSD analysis with SRSS mode combination method is clearly superior in terms of speed and memory usage.[8] The response in the direction of excitation (UY) is captured well with SRSS, although, as noted in Section 4, response in other directions may not necessarily be as accurate. The CQC combination method includes the 'coupling' effect of modes, so it does capture responses in all directions well but at the expense of increased computation time. Generally speaking, however, it is still more efficient than PSDCOM if the number of included modes is not too high (the case of 12-13 modes is fast, but the case of 49 modes is much less efficient).

An interesting thing to note for the "oilpan1" case is that, while the displacements are predicted reasonably well, the maximum RMS SEQV values do not match as well. This is explained partially by the fact that, at 8.1, the SEQV values from PSD analyses represent statistical RMS values whereas the SEQV values from SPRS-type of PSD analyses are simply direct combinations from 1-sigma component values. Although stress components are assumed to have a normal distribution with zero mean, the equivalent stress will not have the same distribution. PSD analyses at 8.1 account for this whereas SPRS-type of PSD analyses do not (so are less accurate), so the values cannot be compared directly.[9]

The SPRS-type of PSD calculation provides a very effective means of performing random vibration analyses. Moreover, when used with the SRSS mode combination method, it can also be used as an efficient means of establishing a "first-pass" preliminary calculation before undertaking a more comprehensive PSD analysis.

6. Conclusion:

The above discussion provides the user frequently running PSD analyses with a few ideas on obtaining more efficient solutions, especially for the situation of single base excitation with a flat spectrum, although some of the points discussed are suitable for other types of random vibration analyses. Some of the aforementioned methods can also be combined together.

The methods discussed above may be useful for initial analyses, in order to get approximate answers quickly. A more comprehensive PSD analysis can then be performed for later runs, once the model is fine-tuned.

[8] The above benchmark includes the time it takes to perform load case combinations when reading in the .mcom file.

[9] For postprocessing PSD results, see "STI04 – PSD Postprocessing" for details.

A. Undocumented Option for Numerical Integration:

As mentioned in Section 3, ANSYS uses closed form integration for the calculation of the modal covariance terms. However, it is possible to switch to numerical integration of covariance terms through undocumented options. This appendix is only meant for advanced users who are aware of what they are doing, as these commands are not recommended for regular use.

- SPOPT,PSD,*NMODE,Elcalc,FRATIO,SIGNIF,IntKey,IntArr,*NUME
  The SPOPT command has five undocumented arguments.
  "FRATIO," or "frequency ratio for modal coupling," limits covariance cross-terms by allowing the user to provide a ratio of the frequency of two modes to be included. For example, specifying FRATIO as "1" will only include diagonal terms of the covariance matrix. This is yet another option of reducing mode combination, as discussed in Section 3, although this requires numerical integration to be turned on (see next).
  For numerical integration, the last four arguments apply. The last argument should be "NUME" to activate numerical integration. The other three options relate to the "integration significance level," "integration key (value of 1 to 6)," and "work array length (value of 100 to 500)," although these are optional and need not be specified. Note that if numerical integration is used, the RPSD calculations in /POST26 will not work properly.
- PSDRES,*Lab,RelKey,WriteRPSD*
  The PSDRES command has an undocumented 3rd argument which, when set to "ON", will write an .rpsd file containing modal response PSDs. The contents of the file may be viewed in /AUX2, although the format is not documented.

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Sheldon's ANSYS.NET Tips and Tricks is available at the following URL:

http://ansys.net/ansys/?mycat=search&mytype=Tips&mycategory=Sheldon

These tips are written with the latest version of ANSYS in mind (version 8.1, as of the time of this writing). Please remember that, with each new release of ANSYS, new features and methods may be introduced, so please refer to the online help as well as your local ANSYS support distributor to verify that these tips are the most efficient way of doing things.

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The XANSYS mailing list is a forum for exchanging ideas, providing/receiving assistance from other users, and general discussions related to ANSYS. (Note that it is recommended to contact your local ASD for issues related to technical support) You can sign up by visiting the following URL:

http://www.xansys.org/mailman/listinfo/xansys

Because the amount of emails is very large, you can also subscribe in "digest mode" or access the postings via a web browser instead:

http://www.xansys.org/mailman/private/xansys/