Simulating Enforced Motion in Ansys Structural Dynamic Problems

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Background

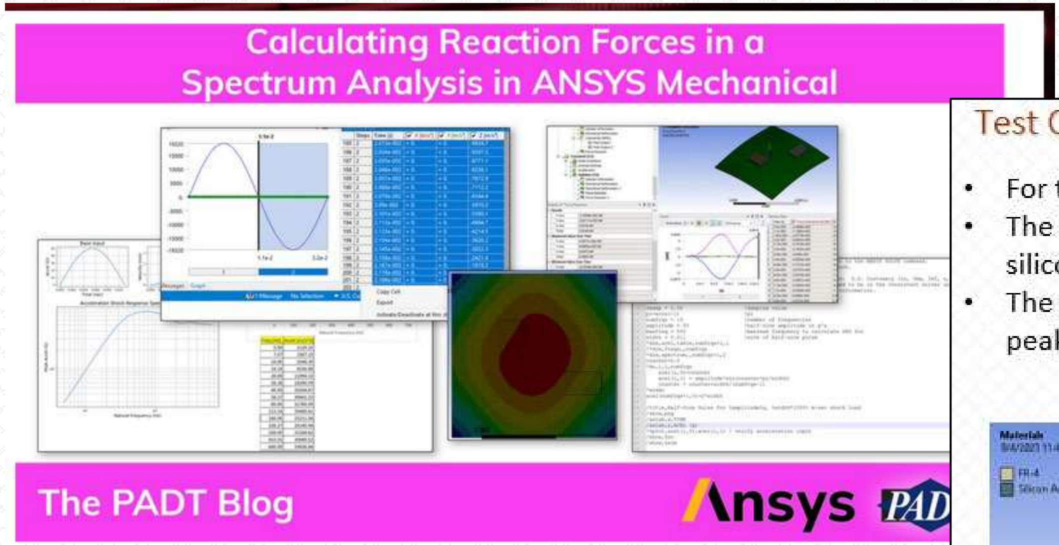
- Most users of Ansys will be familiar with the classical solution of a harmonic oscillator subject to base motion (if not, see here)
- However, until Ansys version 12.1 (2010), users were restricted to the following methods and use cases when analyzing such motion:

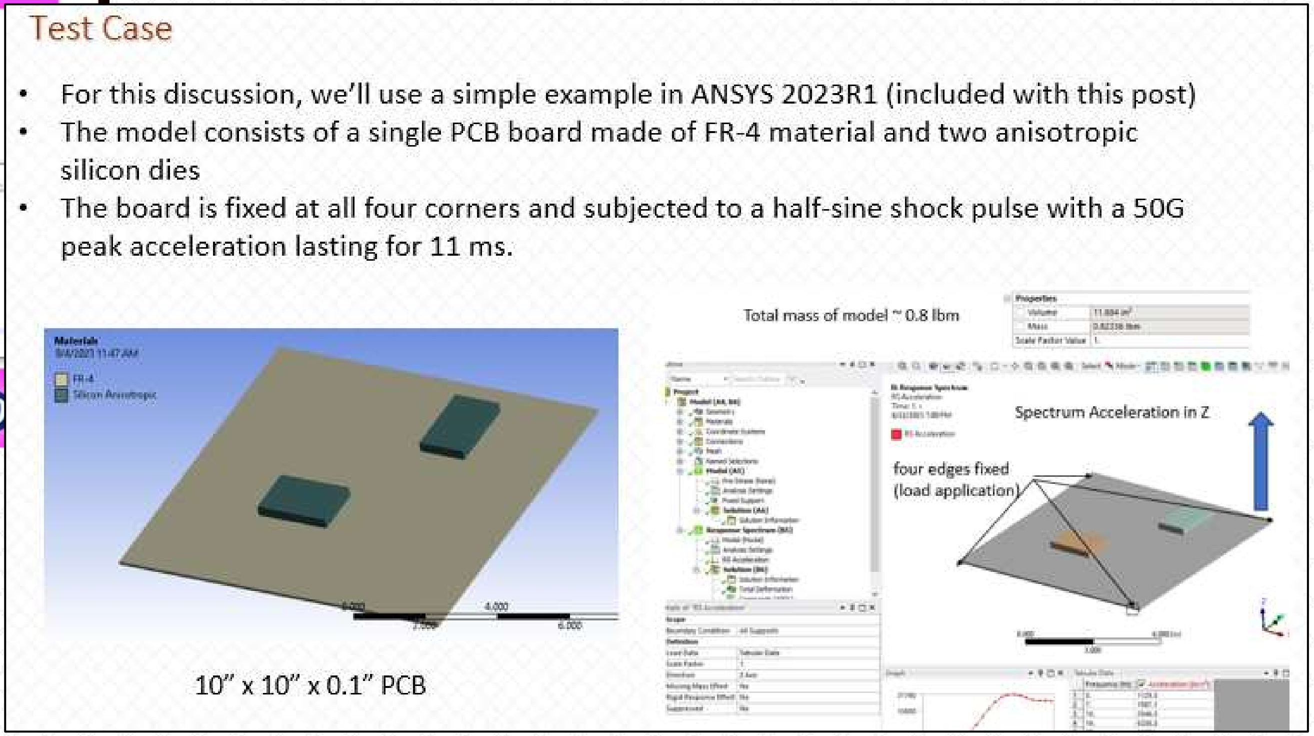
1. **Mode-Superposition Harmonic and Transient Analysis:** Base-Relative motion only. Eigenvalues restricted to zero motion at modal boundary condition. In this scenario, enforced motion cannot be applied directly, but rather as an acceleration body load only. Response values are thus base-relative.
2. **Full Harmonic and Transient Analaysis:** Option 1: Same as above. Option 2: Apply a nonzero base displacement loading (MAPDL 'd' command with the following options: ux,uy,uz,velx,vely,velz,accx,accy,accz)
3. **Random Vibration:** Users input a frequency-dependent base power spectral density, and then select whether the solution is absolute or base-relative
4. **Shock Spectrum Analysis:** All enforced motion spectra are base relative (as in 1)

- Starting at release 12.1, at least the item 1 above has changed (base motion may be simulated directly using mode-superposition in either a base-relative or absolute reference frame)
- Items 3 and 4 above are straightforward and haven't changed since the author started using Ansys. However, use-cases 1 and 2 are poorly understood by most users of Ansys and Workbench today (2024), so we'll discuss those in this article

The Model

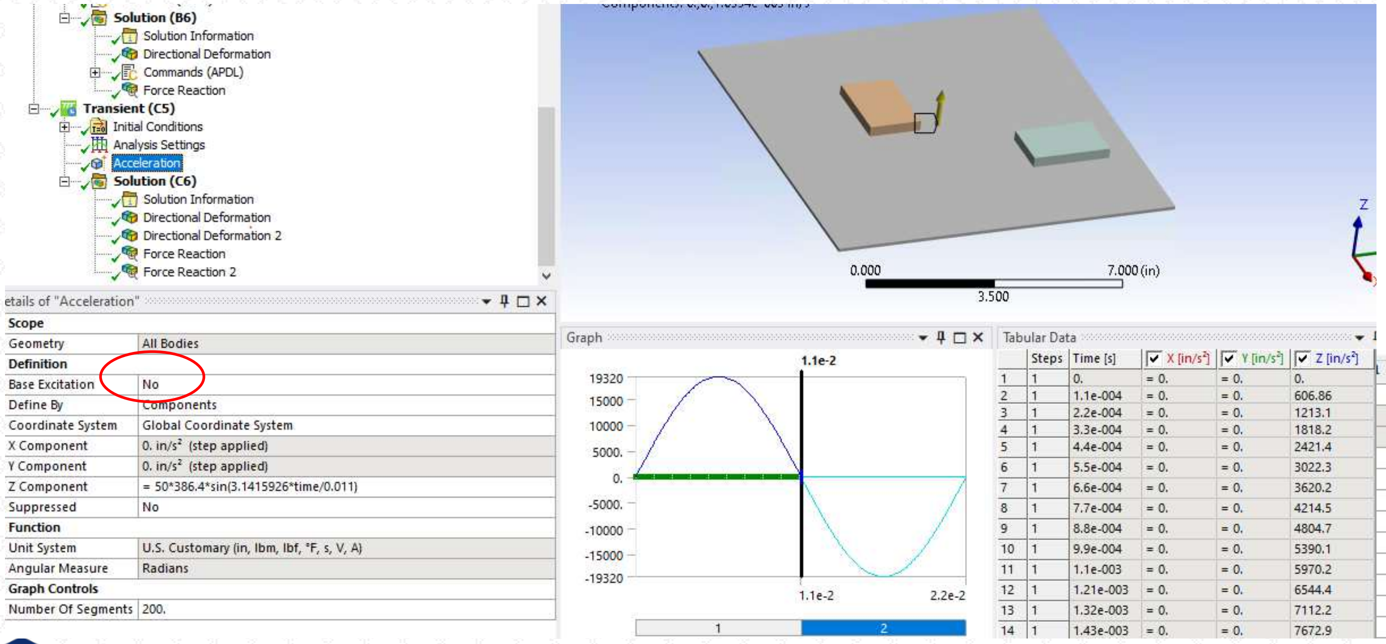
- As mentioned, starting at Ansys release 12.1 (2010), Ansys added the ability to simulate base (enforced) motion directly
- Few users seem aware, however, that both use cases 1 and 2 may both be easily accessed in Ansys Workbench using the same simple interface.
- To demonstrate this, we'll re-use the model we introduced in [this previous blog post](#) (an example of use-case 4)

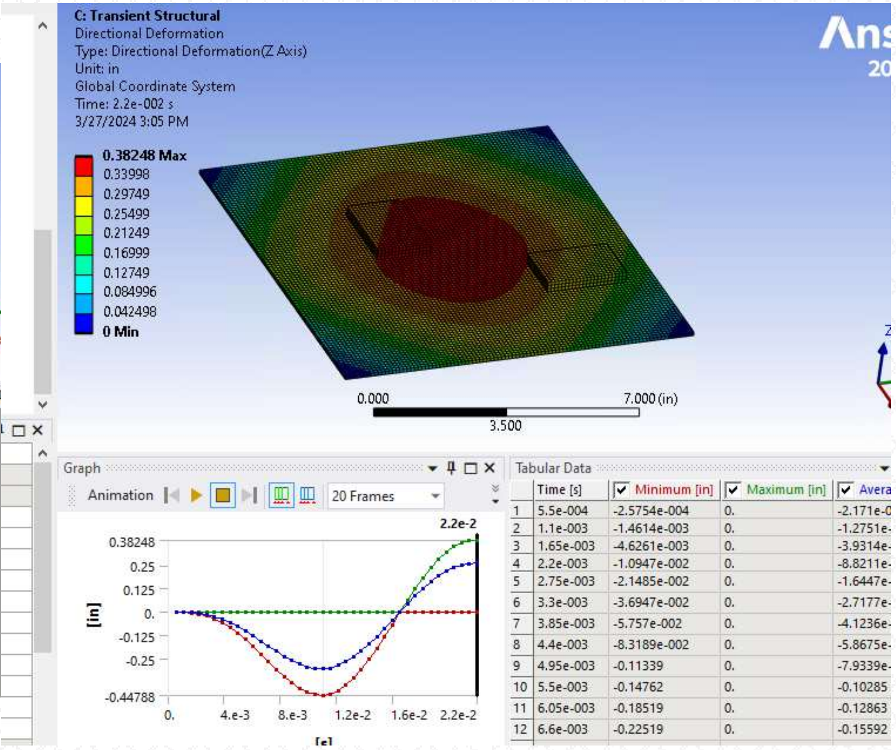




Acceleration Load: The ‘Base Excitation’ Field

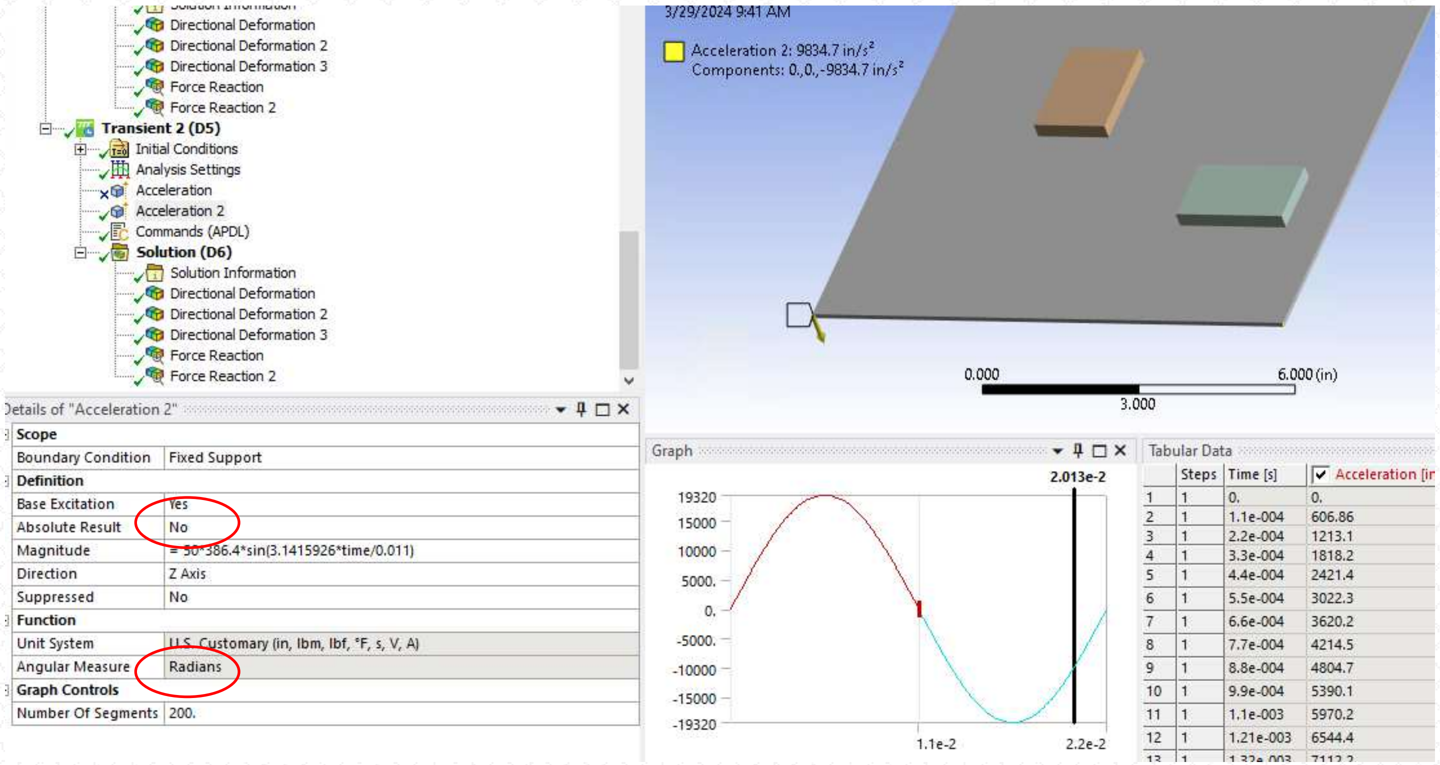
- After downloading the 2023R1 Ansys model (see the notes after this PDF in this blog post) from the previous blog post link, open (edit) the Transient Structural system in Mechanical
- Take a close look at the Acceleration load. Notice that the ‘Base Excitation’ field is set to ‘No’. This is the default, and most users find this confusing. Particularly because this IS a ‘base-relative’ solution (as we’ll see in a moment
- It is an acceleration body load applied to a fixed base, and the displacement response is relative to this fixed base (contour plot at lower right)





Base Excitation (Yes): Absolute Result (No)

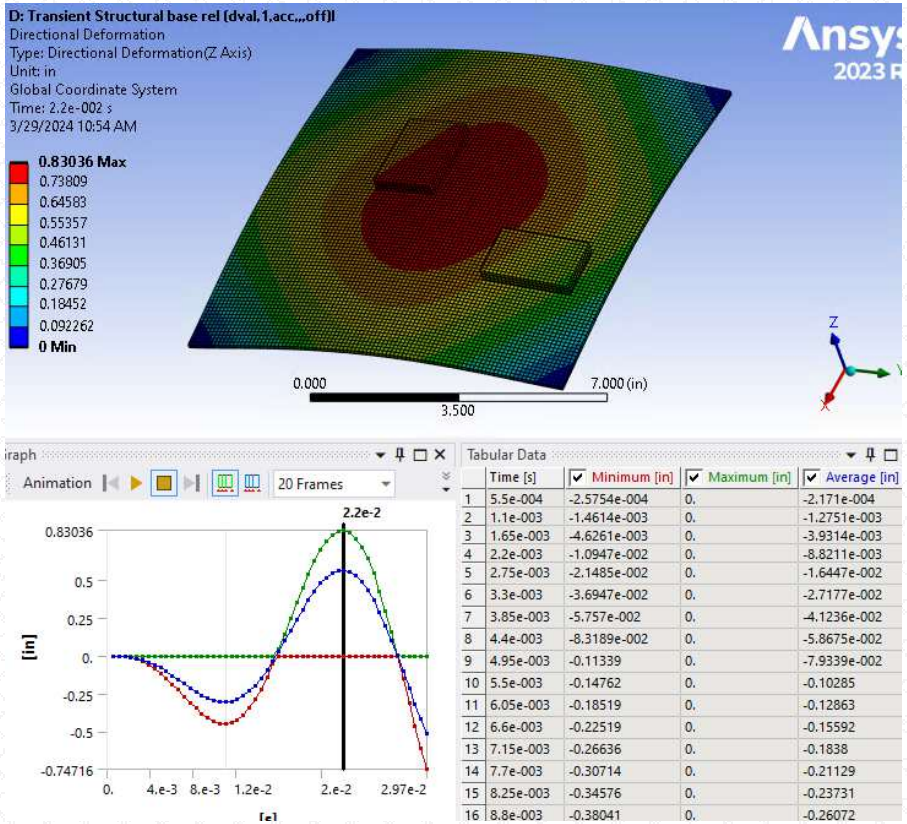
- We're going to set 'Base Excitation' to 'Yes'. Make note of the parameters of the sine table. It's easiest if you copy it before modifying the base excitation type). Note that you may have to delete the 'Acceleration' load and recreate it if the angular measure has been reset to 'degrees' (changing the units won't update the angular measure for this load)



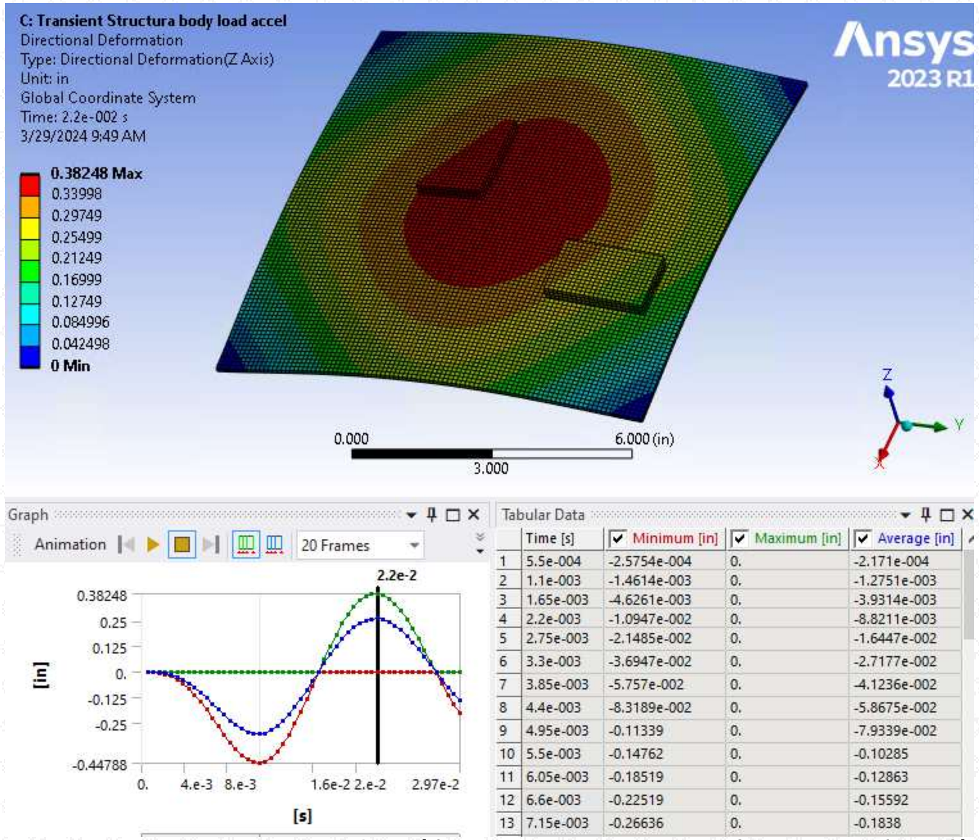
- Make sure that 'Absolute Result' is set to 'No'
- This should produce results identical with those we had before, but achieved by solving a slightly re-arranged set of equations

Base Excitation (Yes): Absolute Result (No)

- Run the model and compare to to the results of the previous blog post for the half-sine pulse (note that you may have to re-run the modal analysis)
- The first thing we notice is that they're NOT the same!
- What's going on?



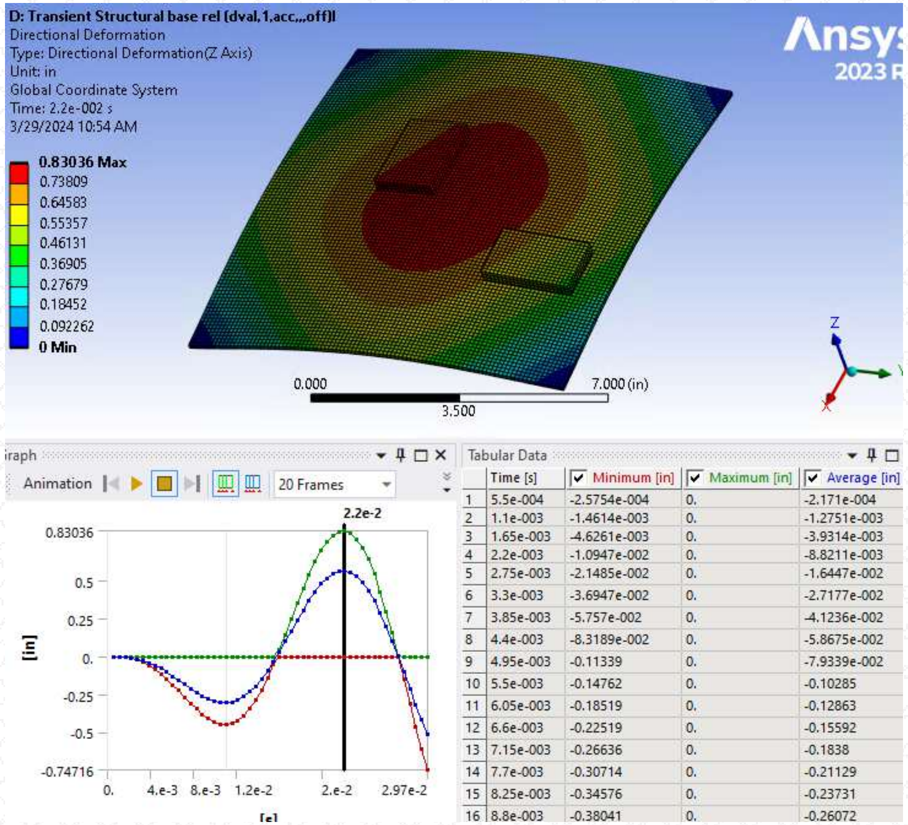
New results ('Base Excitation' set to 'Yes')



Previous results ('Base Excitation' set to 'No')

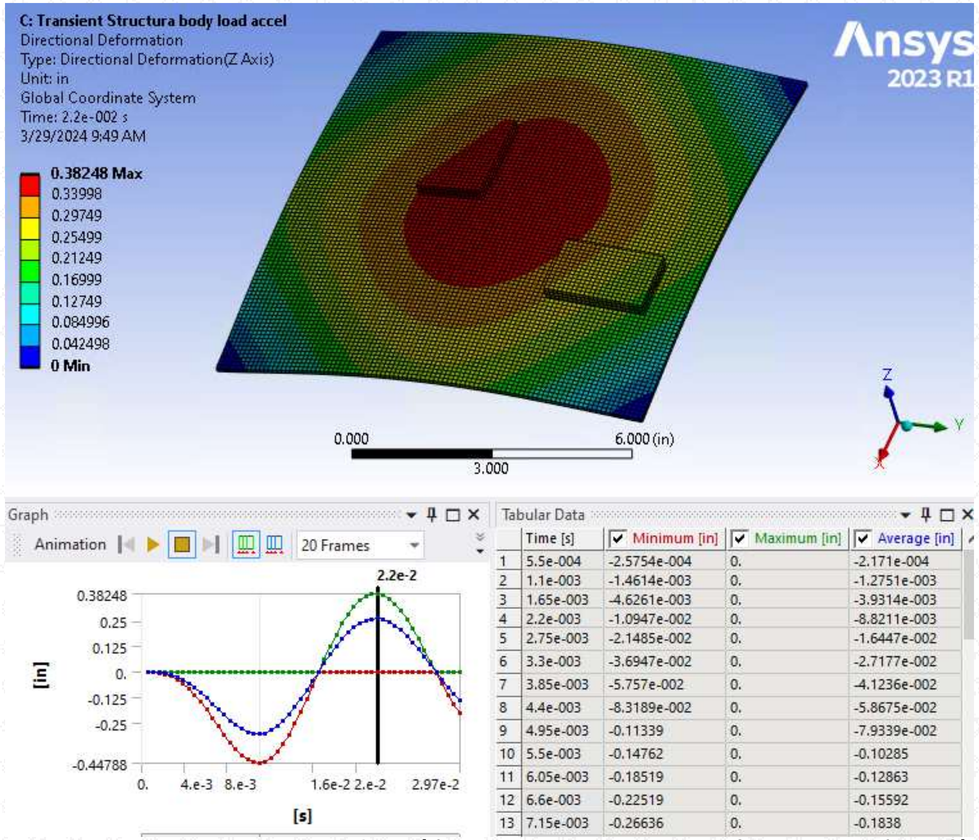
Base Excitation (Yes): Absolute Result (No)

- The smoking gun in this case is that the maximum displacement reponse occurs at the very end of the run time –in violation of our loading (which ends at 0.011s)
- The maximum response must occur WITHIN the fundamental period (0.022s) when loading ends before that (not at the very end as is occuring in the new result)



	Time [s]	Minimum [in]	Maximum [in]	Average [in]
1	5.5e-004	-2.5754e-004	0.	-2.171e-004
2	1.1e-003	-1.4614e-003	0.	-1.2751e-003
3	1.65e-003	-4.6261e-003	0.	-3.9314e-003
4	2.2e-003	-1.0947e-002	0.	-8.8211e-003
5	2.75e-003	-2.1485e-002	0.	-1.6447e-002
6	3.3e-003	-3.6947e-002	0.	-2.7177e-002
7	3.85e-003	-5.757e-002	0.	-4.1236e-002
8	4.4e-003	-8.3189e-002	0.	-5.8675e-002
9	4.95e-003	-0.11339	0.	-7.9339e-002
10	5.5e-003	-0.14762	0.	-0.10285
11	6.05e-003	-0.18519	0.	-0.12863
12	6.6e-003	-0.22519	0.	-0.15592
13	7.15e-003	-0.26636	0.	-0.1838
14	7.7e-003	-0.30714	0.	-0.21129
15	8.25e-003	-0.34576	0.	-0.23731
16	8.8e-003	-0.38041	0.	-0.26072

New results (‘Base Excitation’ set to ‘Yes’)



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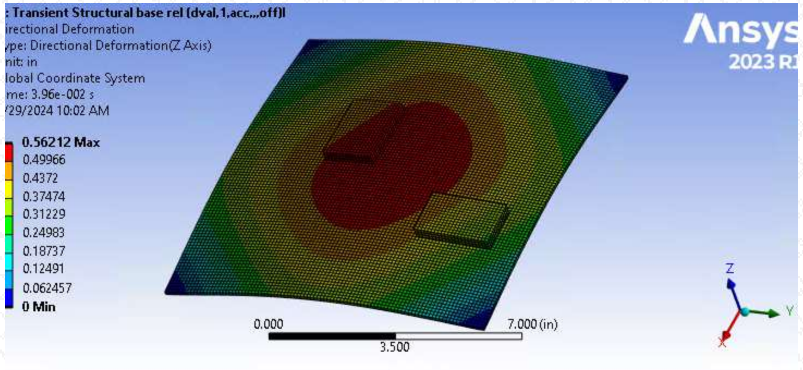
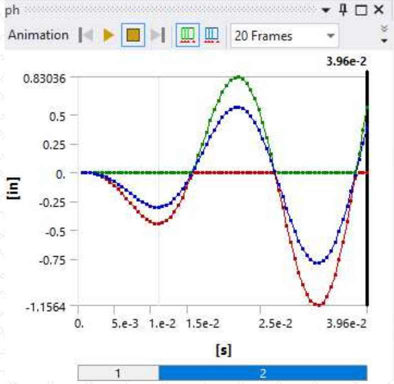
6	3.3e-003	-3.6947e-002	0.	-2.7177e-002
7	3.85e-003	-5.757e-002	0.	-4.1236e-002
8	4.4e-003	-8.3189e-002	0.	-5.8675e-002
9	4.95e-003	-0.11339	0.	-7.9339e-002
10	5.5e-003	-0.14762	0.	-0.10285
11	6.05e-003	-0.18519	0.	-0.12863
12	6.6e-003	-0.22519	0.	-0.15592
13	7.15e-003	-0.26636	0.	-0.1838

Previous results (‘Base Excitation’ set to ‘No’)

Base Excitation (Yes): Absolute Result (No)

- We can see the problem more clearly if we run the analysis over a longer time span. Modifying the end time to be 0.04s (instead of 0.03s), we see that the displacement response continues to grow!
- It appears that the load deactivation is not getting implemented properly
- This can be verified by inspecing the ds.dat file in the solver files directory (near the end)





Tabular Data

	Time [s]	Minimum [in]	Maximum [in]	Average [in]
1	5.5e-004	-2.5754e-004	0.	-2.171e-004
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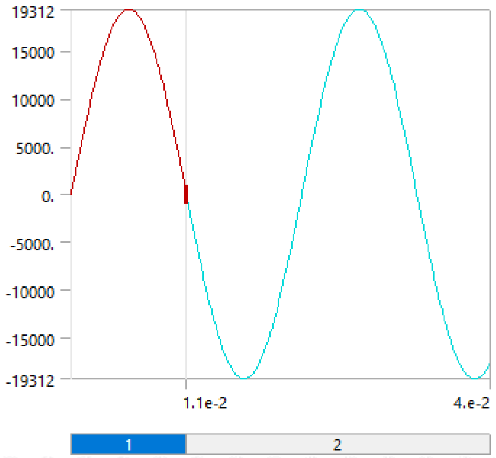
15	8.25e-003	-0.34576	0.	-0.23731
16	8.8e-003	-0.38041	0.	-0.26072
17	9.35e-003	-0.40943	0.	-0.28036
18	9.9e-003	-0.43128	0.	-0.29509

New results (‘Base Excitation’ set to ‘Yes’)

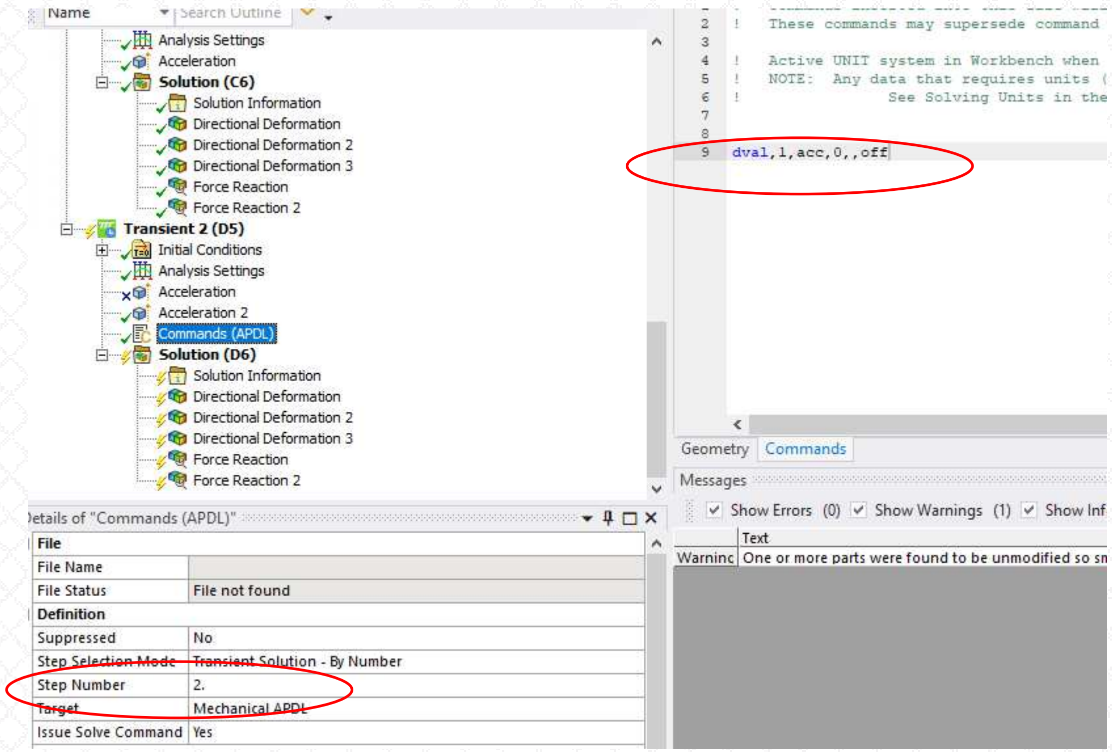


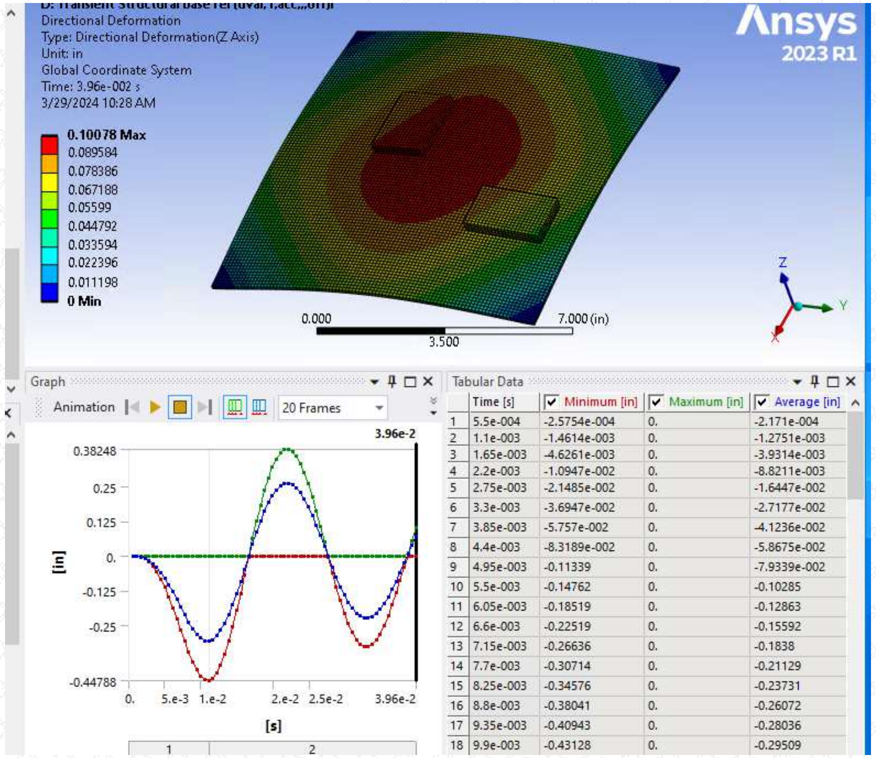
- Load step 2 should have a zero load
- But the ‘dval’ coommand here continues to apply the sine function loading

```
/com,*****************************************************
/com,*************** FINISHED SOLVE FOR LS 1 *************
time,4.e-002
fdele,all,all
sfdele,all,all
sfedele,all,all,all
acel,0,0,0                    ! zero out the acceleration
/com,*********** Applying Base Excitation(s) ***********
dval,1,acc,%_loadvari381z%,,off
outres,erase
outres,all,none
outres,nsol,all
solve
```

Base Excitation (Yes): Absolute Result (No)

- This is likely a problem restricted to ‘function’ loading.
- We originally chose to implement the half-sine impulse using a function for convenience (instead of generating the loading time-history manually).
- Fortunately, there are many ‘workarounds’
- Perhaps the simplest is to insert a single one-line ‘Commands’ object to force deactivation of the load (by overriding the ‘dval’ command at load step 2 with a zero load).

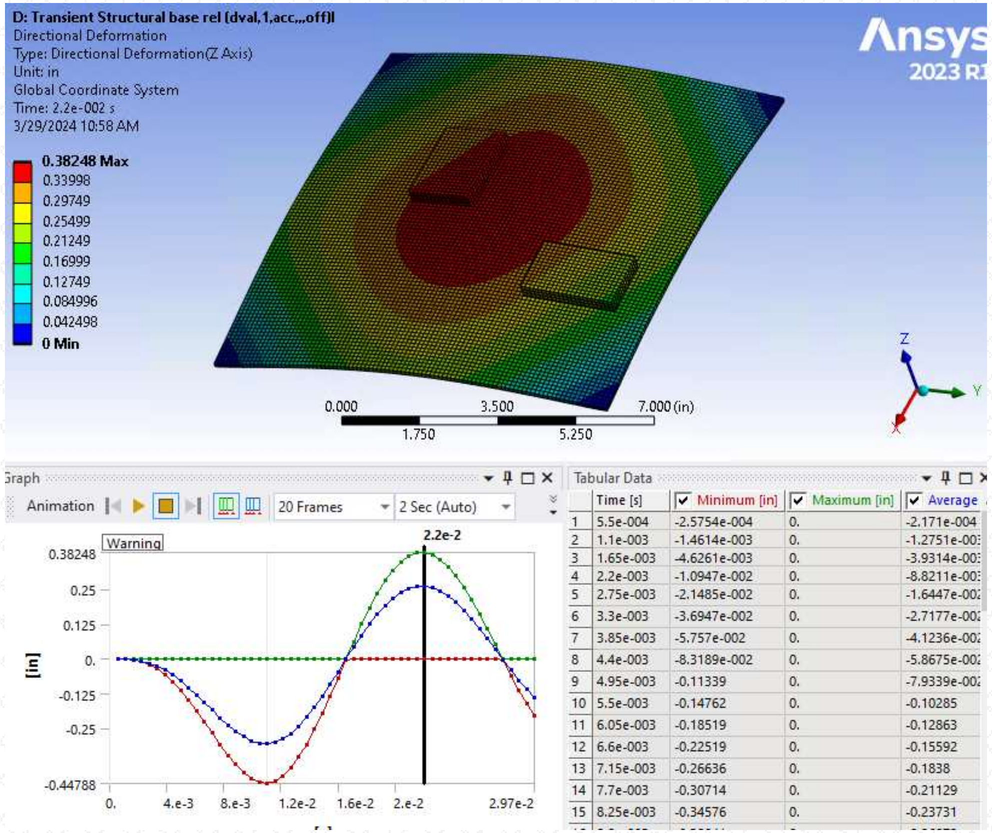




- These results look correct!

Base Excitation (Yes): Absolute Result (No)

- After resetting the end-time back to the orginal 0.03s, we can do a side-by-side comparison with our old results and new results with load correction.
- The results now match to within the available precision!



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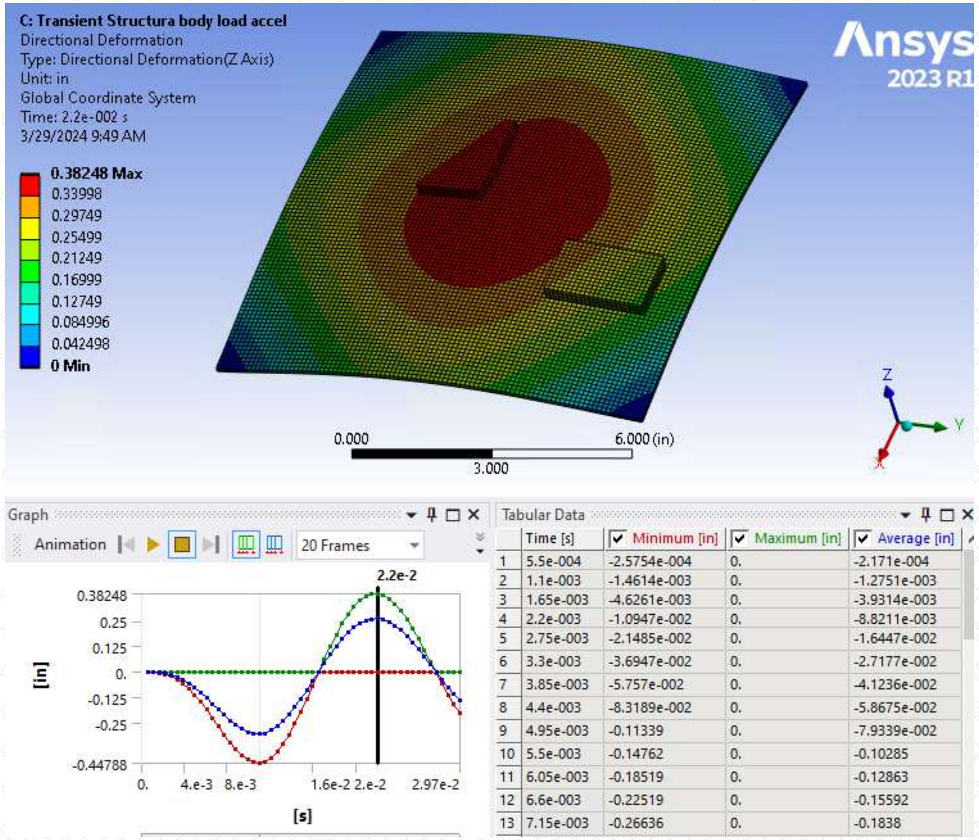
14	7.7e-003	-0.30714	0.	-0.21129
15	8.25e-003	-0.34576	0.	-0.23731

New results (‘Base Excitation’ set to ‘Yes’. Corrected Load)



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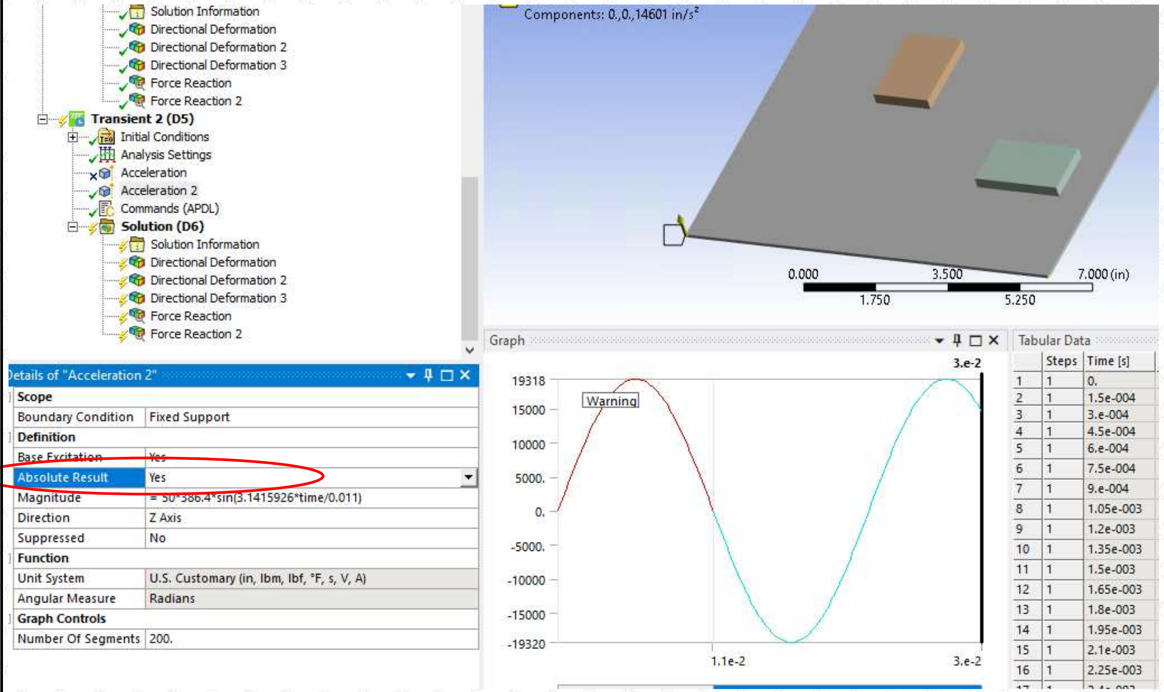
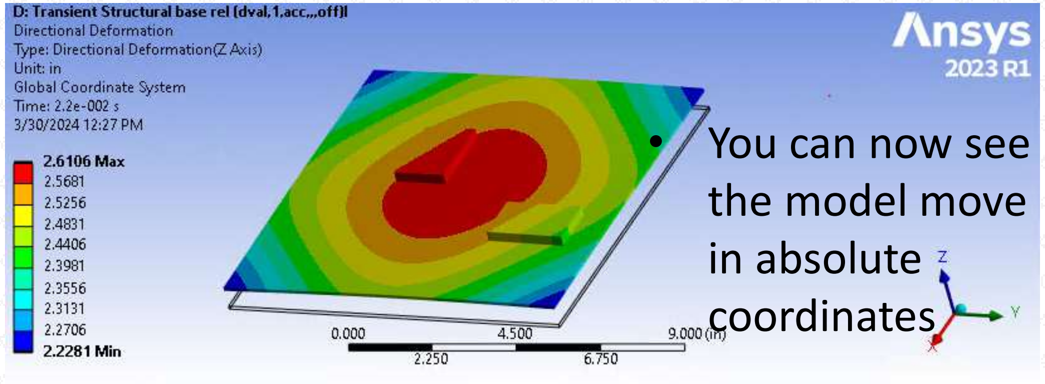
Previous results (‘Base Excitation’ set to ‘No’)

Base Excitation (Yes): Absolute Result (Yes)

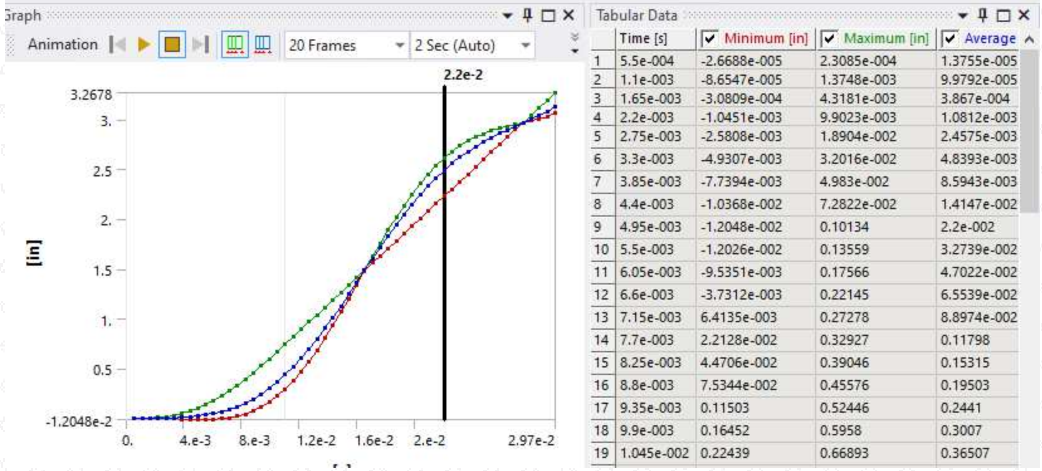
- Now, set 'Absolute Results' to 'Yes' to see the results in absolute (inertial) coordinates
- Modify the 'Commands' object created earlier to use absolute coordinates
- In inertial coordinates (below right), the corners have traveled 2.22 inches in Z at 0.022s (3 inches at 0.03s)




```
8
9 dval,1,acc,0,,on
```



- You can now see the model move in absolute coordinates



New results ('Base Excitation' set to 'Yes'.'Absolute Result' set to 'Yes'. Corrected Load)

Base Excitation: Checking Absolute Results

- By setting ‘Absolute Result’ to ‘Yes’, we can actually see the model’s motion within an ‘absolute’ (inertial) reference frame. In other words, we can now see it move, whereas all previous results were with respect to a moving base
- This is the point of ‘enforced’ motion. We are actually applying some time derivative of displacement to the base --instead of applying acceleration as a body load. And through simple algebraic manipulations (see the DVAL command), we are given the option of whether the result should be interpreted in absolute (non-moving) coordinates, or not. When the acceleration is applied as a body load, we don’t have this choice (all results will be base-relative in that case).
- We can use the simple relationship between base-relative and absolute results to verify the absolute result
- To simplify matters, consider only a single applied base excitation (as in this study. The DVAL command is meant to handle more complicated loading) to the 2 DoF system below (this extends easily to an arbitrary number of DoFs)...

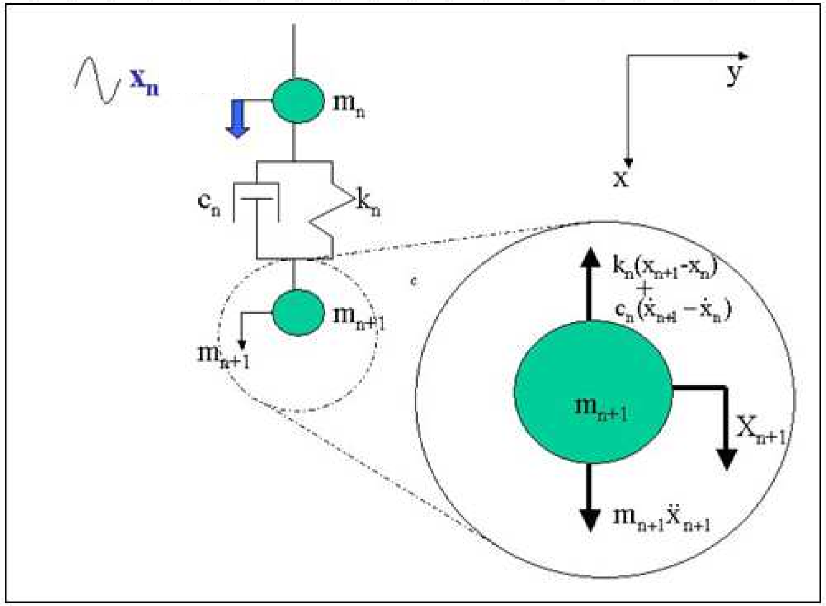
- A force balance on DoF n+1 (the free DoF) with no applied load yields:

$$m_{n+1}\ddot{x}_{n+1} + c_n(\dot{x}_{n+1} - \dot{x}_n) + k_n(x_{n+1} - x_n) = 0 \qquad (1)$$

- Now, just subtract $m_{n+1}\ddot{x_n}$ from both sides:

$$m_{n+1}(\ddot{x}_{n+1} - \ddot{x}_n) + c_n(\dot{x}_{n+1} - \dot{x}_n) + k_n(x_{n+1} - x_n) = -m_{n+1}\ddot{x}_n \qquad (2)$$

$$or \quad m_{n+1}\ddot{z} + c_n\dot{z} + k_n z = -m_{n+1}\ddot{x}_n$$



Base Excitation: Checking Absolute Results

- In equation (2) of the previous slide, we made the transformation **z**-**x**-$\mathbf{x}_0$
- But this is just $x_{n+1} - x_n$, or the displacement of m_{n+1} (the free DoF) with respect to the DoF with the applied load (the base, n), while the term $m_{n+1}\ddot{x_n}$ is the free mass at n+1 subjected to the applied acceleration, $\ddot{x_n}$ (in other words: a body load)
- Thus, equation (2) gives us a base-relative solution of the 2 DoF system (the motion of m_{n+1} relative to n)
- But the transformation **z**-**x**-$\mathbf{x}_0$ also instantly informs us how to recover the 'absolute' solution, **x**:

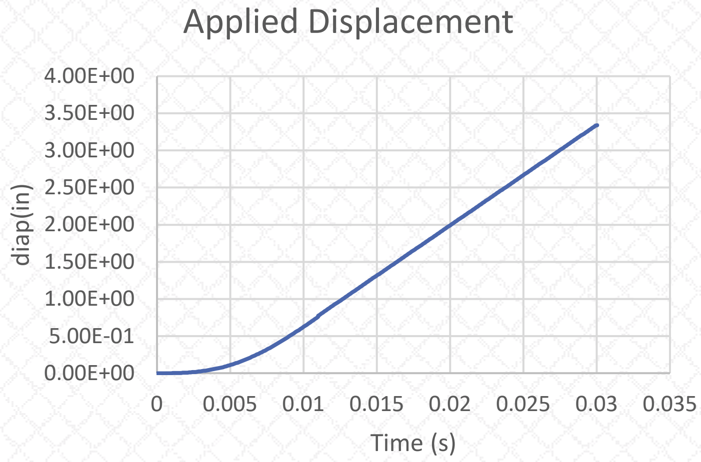
$$\mathbf{x}=\mathbf{z}+\mathbf{x}_0 \qquad (3)$$

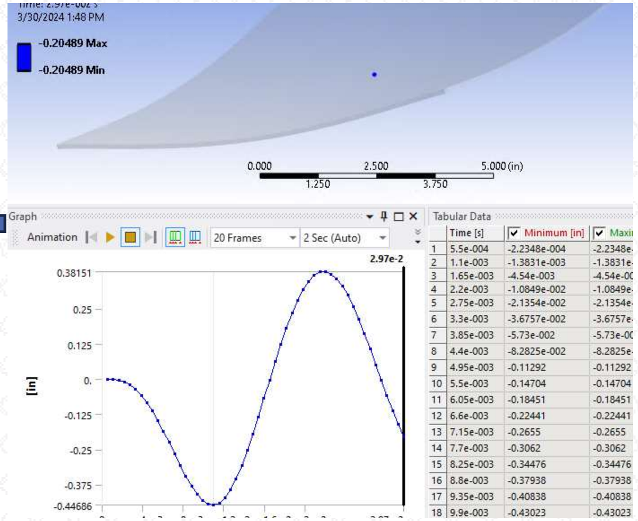
- In other words, the absolute solution should just be the base-relative solution plus the applied displacement
- Even though we applied an acceleration, the equivalent displacement,$\mathbf{x}_0$ may be obtained easily enough by simply integrating the applied motion twice!

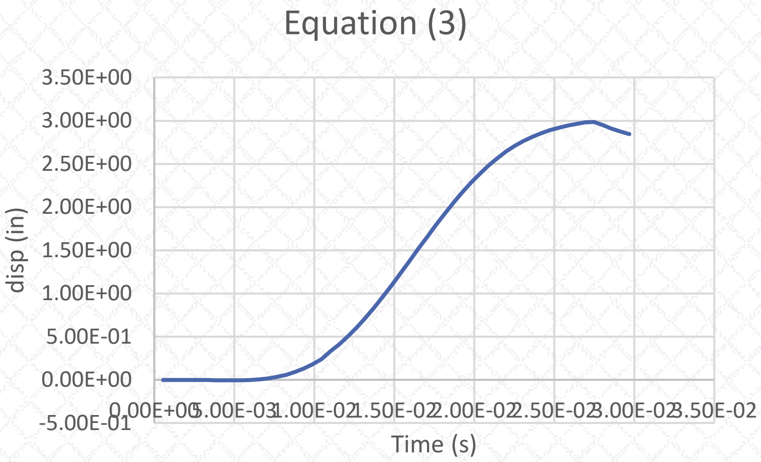
- So, we can use equation (3) to check our new absolute solution

Base Excitation: Checking Absolute Results

- We'll check the absolute displacement result of the center of the plate against what we'd predict using equation (3)
- This is done in the spreadsheet 'response_comparison.xlsx' which accompanies this article
- Below left is the applied base displacement (the half-sine acceleration after being integrated twice with respect to time)
- Below center is the plate center relative displacment (Ansys result with 'Base Excitation' set to 'No')
- Below right is the combination (Equation (3))

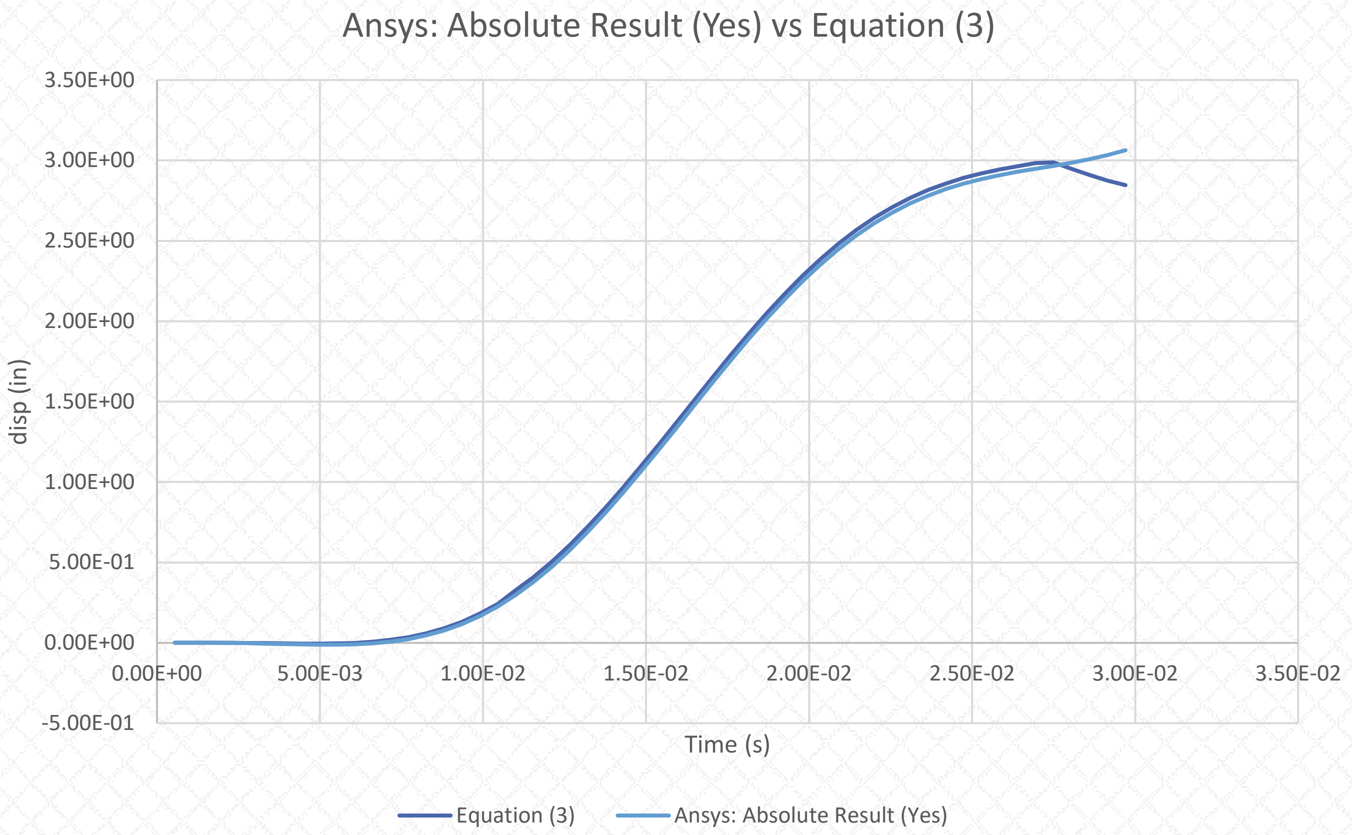






Base Excitation: Checking Absolute Results

- In spite of what appears to happening in the last time step (?), the Equation (3) seems to agree well with the Ansys Absolute Result at the plate center:



The Large Mass Method

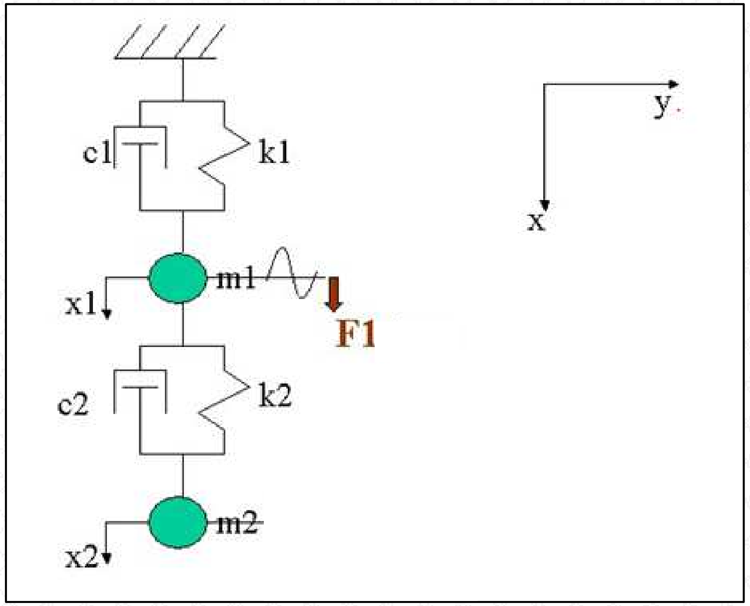
- We may further check our results in absolute coordinates using the 'Large Mass Method' (LMM).
- In this method, a mass, M is attached to the base (@m_1, the degrees of freedom previously fixed), such that M>>m where m is the model total mass, m_1+m_2 (see the documentation on this method, as well as the DVAL command used to apply the base excitation in the previous section. These two concepts go together in the Theory Manual)
- A simple explanation of the LMM may be given with yet another 2-spring-mass system. Starting with the force balance (as before, but this time tracking both DoFs):

$$m_1\ddot{x}_1 + (c_1 + c_2)\dot{x}_1 - c_2\dot{x}_2 + (k_1 + k_2)x_1 - k_2x_2 = F_1 \quad (4)$$

$$m_2\ddot{x}_2 - c_2\dot{x}_1 + c_2\dot{x}_2 - k_2x_1 + k_2x_2 = 0$$

or

$$\begin{pmatrix} m_1 & 0 \\ 0 & m_2 \end{pmatrix}\begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix} + \begin{pmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{pmatrix}\begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} + \begin{pmatrix} c_1 + c_2 & -c_2 \\ -c_2 & c_2 \end{pmatrix}\begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{Bmatrix} = \begin{Bmatrix} F_1 \\ 0 \end{Bmatrix} \quad (5)$$



- The large mass, M is attached to the base, m_1. Substituting this into the first part of (4) and solving for $\ddot{x}_1$:

$$\ddot{x}_1 = \frac{1}{M}(F_1 - (c_1 + c_2)\dot{x}_1 + c_2x_2 - (k_1 + \dot{k}_2)x_1 + k_2x_2) \quad (6)$$

The Large Mass Method

- Now, in the LMM, we're usually trying to approximate some finite (imposed) $\ddot{x}_1$at the base by applying an appropriate load, F_1 . Equation (6) tells us that, as $M \rightarrow \infty$, $F_1 \rightarrow \infty$ in such a way that $F_1 \approx M\ddot{x}_1$. And as this occurs, the fixed terms effectively vanish because:

$$F_1 \gg ((c_1 + c_2)\dot{x}_1 + c_2 x_2 - (k_1 + k_2)x_1 + k_2 x_2) \qquad (6)$$

- therefore, as $M \rightarrow \infty$:

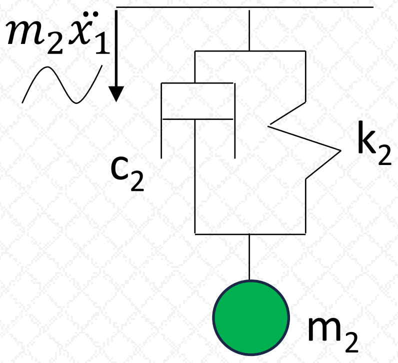
$$M\ddot{x}_1 = (F_1 - \cancel{(c_1 + c_2)\dot{x}_1 + c_2 x_2 - (k_1 + k_2)x_1 + k_2 x_2})$$

these terms become negligible with respect to F_1

- Rearranging the second equation in (4):

$$m_2\ddot{x}_2 + c_2\dot{x}_2 + k_2 x_2 = c_2\dot{x}_1 + k_2 x_1 \qquad (7)$$

- But as $M \rightarrow \infty$, the equations (4) and (5) become effectively uncoupled. And so the right-hand side of (7) becomes equal to $-m_2\ddot{x}_1$ (in other words, the RHS is equivalent to another fixed spring-mass system with a fixed base and displacement x_1 whose mass accelerates with a value of $\ddot{x}_1$. This equivalence allows us to instead prescribe the motion $-m_2\ddot{x}_1$)



$$m_2\ddot{x}_2 + c_2\dot{x}_2 + k_2 x_2 = -m_2\ddot{x}_1 \qquad (8)$$

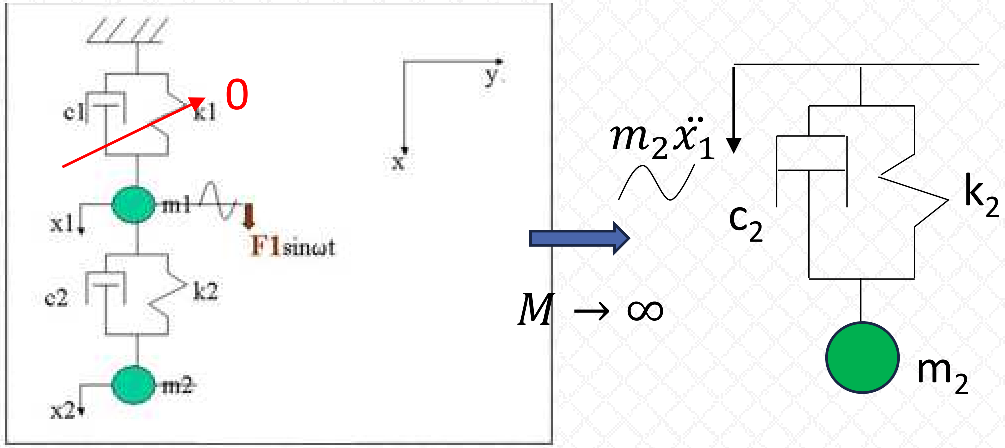
The Large Mass Method

- For a more detailed mathematical analysis of exactly how the degrees of freedom become decoupled, see here . In any case, as $M \to \infty$, equations (4) and (5) appoximate the equations below

$$M\ddot{x}_1 = F_1$$
$$m_2\ddot{x}_2 + c_2\dot{x}_2 + k_2x_2 = -m_2\ddot{x}_1 \qquad (9)$$

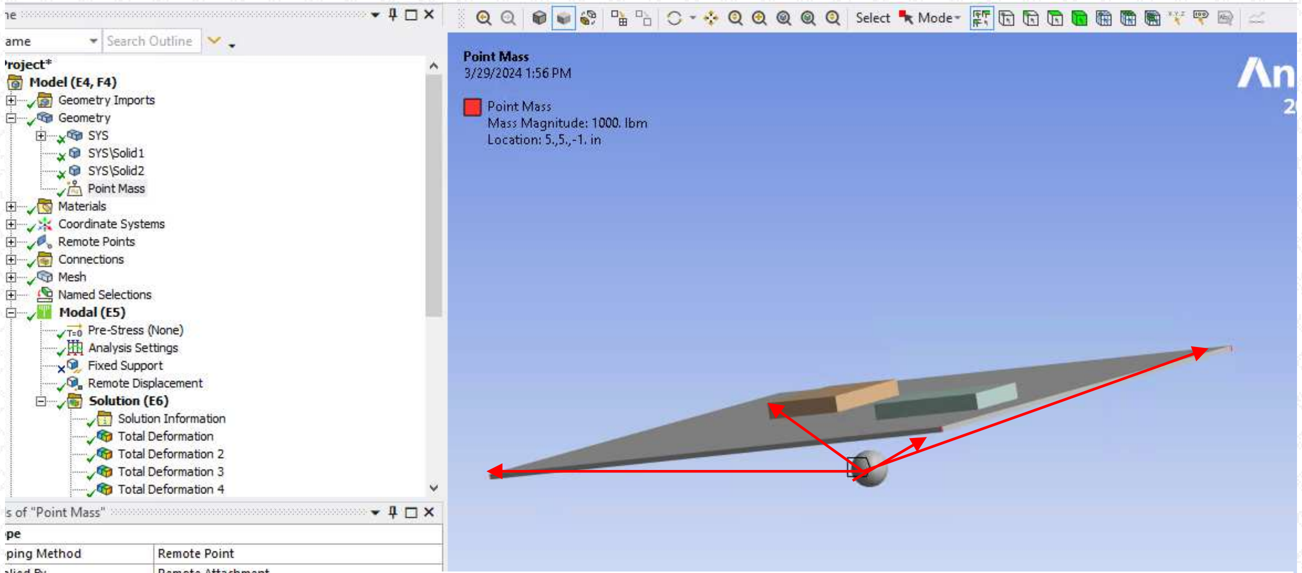
- Comparing this with equation (2), we see that we can convert equation (2) to equation (9) via the transformation (3)

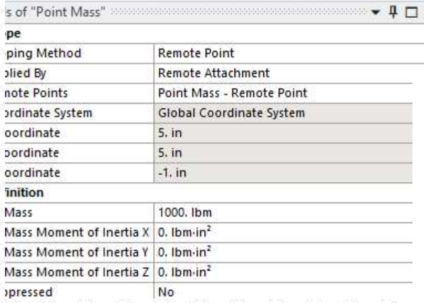
- We've taken some liberties in this derivation for the sake of algebraic clarity. In particular, what we're calling the 'base' (DoF 1) is fixed (grounded) in our diagram (which need not be the case in general. We've done this deliberately to stay in inertial coordinates). But as M becomes sufficiently large, the fundamental frequency $\sqrt{k_1/M} \to 0$ (this will show up as a new rigid-body mode in our modal analysis).
- In this way, any grounding spring connections effectively disappear.



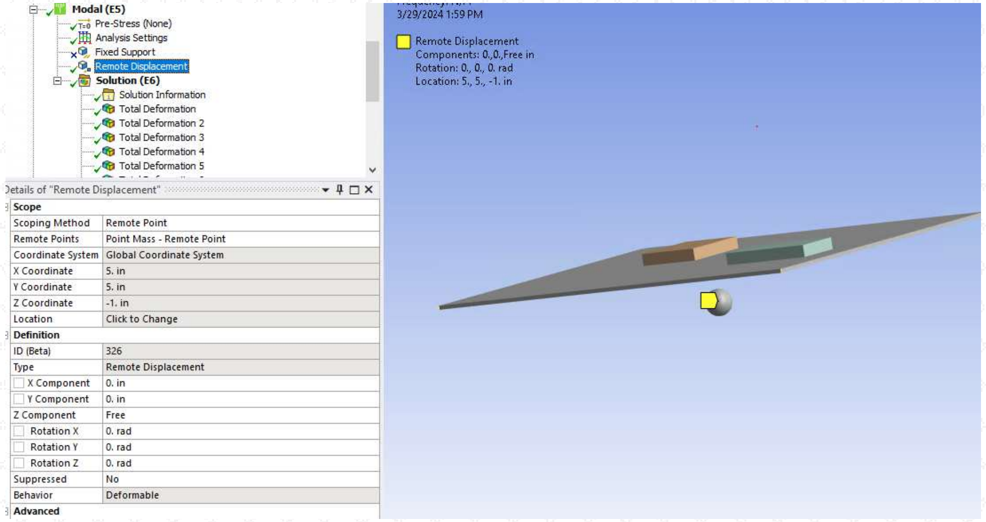
The Large Mass Method

- We’ll use a mass of 1000 lbm (Most guides suggest using a value between 10e4 to 10e8 times the model mass)





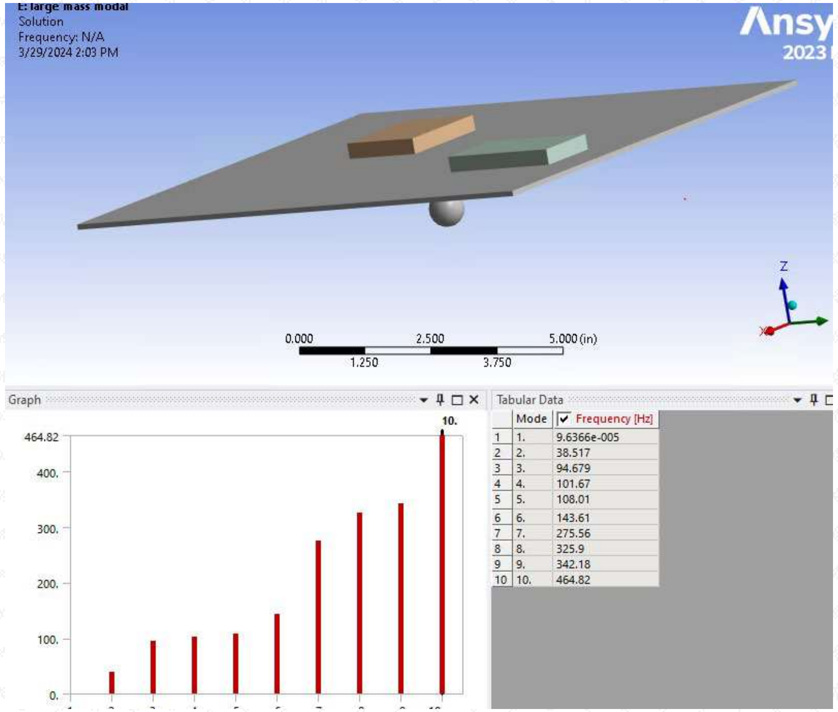
- attach mass to the four corners previously fixed
- Promote to ‘remote point’ to apply boundary conditions to the mass
- Attach the mass with ‘rigid’ connections



- Fix all degrees of freedom of the large mass (remote point), except the loading direction (z)

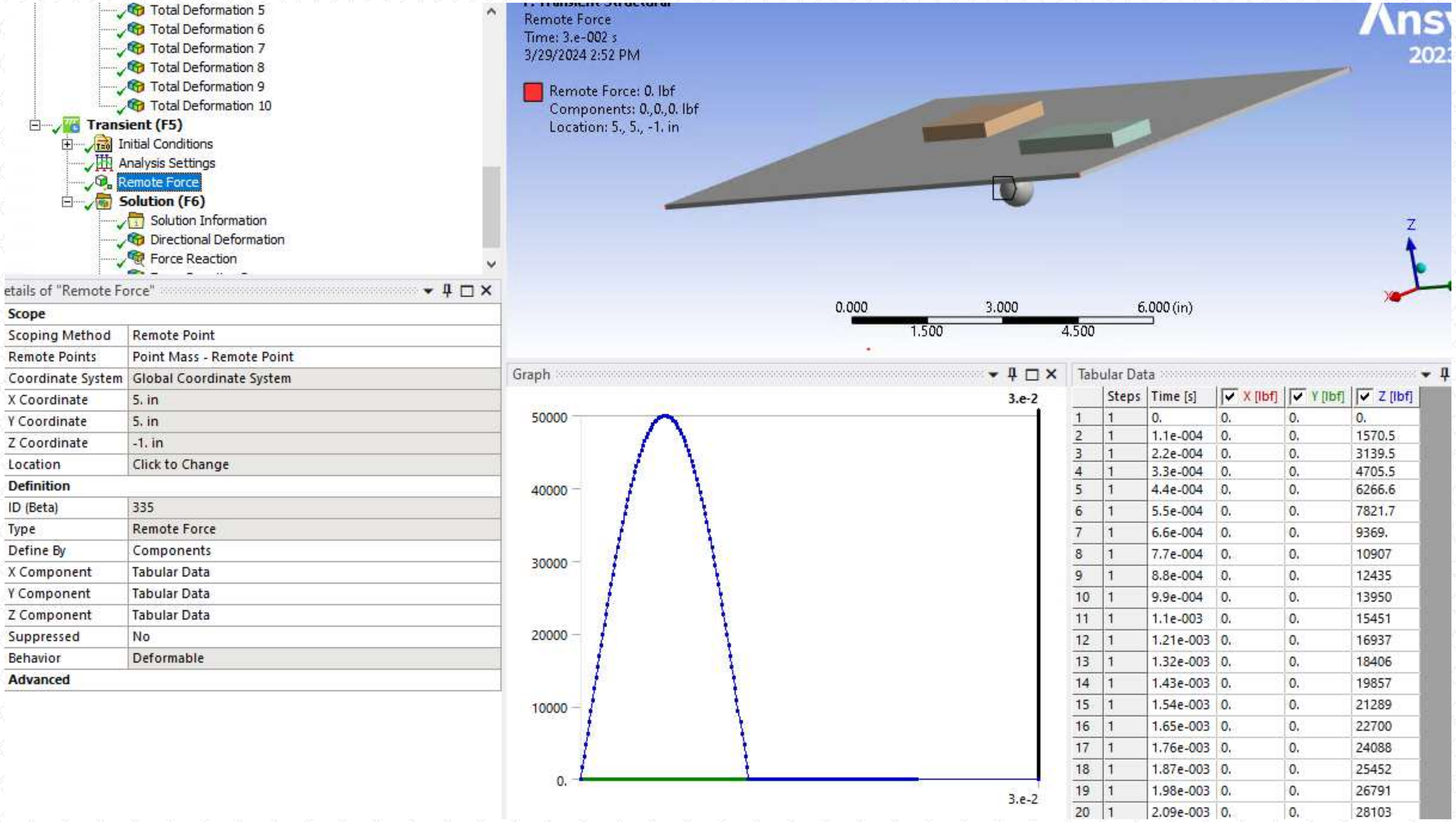
The Large Mass Method

- Running the modal analysis for the model with large mass introduces a new fundamental rigid body mode
- The rigid body mode is crucial for applying the load
- Note also that the modes have changed somewhat. In particular, the previous fundamental mode (45.87 Hz) has dropped to 38.5 Hz. This is happening mostly because we have only one element through the board thickess (the mass is attached to only 8 nodes – 2 for each edge of the four corners). Increasing the mesh refinement, as well as increasing the mass value further, should suffice to increase mode 2 to a value much closer to teh original 45.87 Hz.
- We won't do this for this study (our results will be close enough to verify the model)



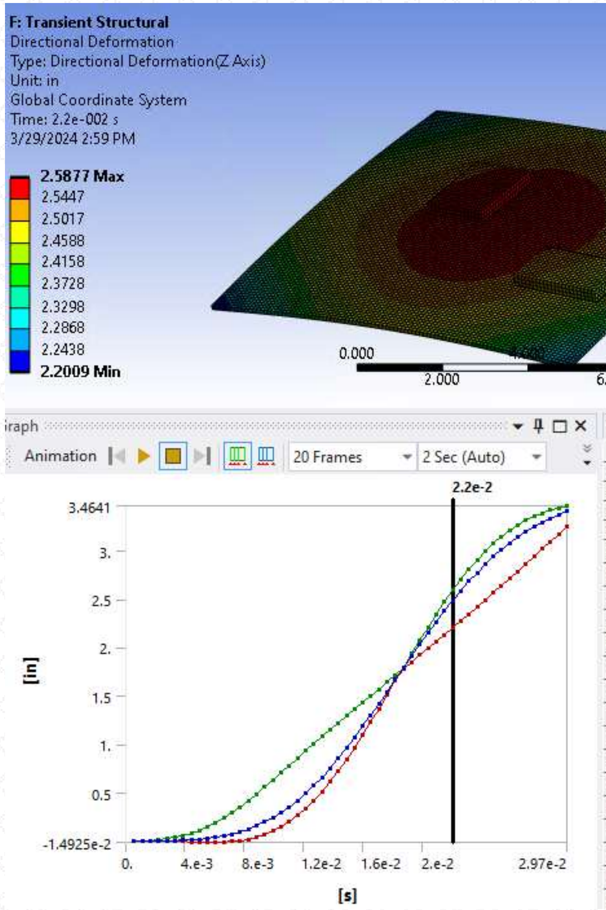
The Large Mass Method

- Finally, we apply a remote force sufficient to accelerate the model with the half-sine pulse as before (using F = Ma, where M is the large mass and a is the half-sine acceleration) in a downstream mode-superposition-based transient study



The Large Mass Method

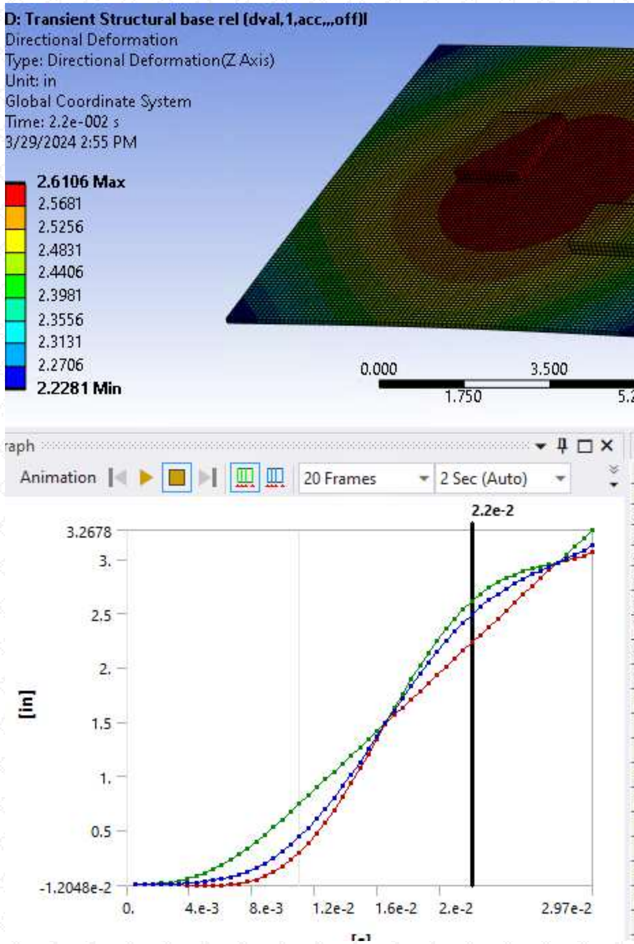
- Now, run the model and compare results to the base excitation with ‘Absolute Results’ set to ‘Yes’.
- Again, we’re comparing results at the end of the fundamental period of excitation (0.022s)



Tabular Data

	Time [s]	Minimum [in]	Maximum [in]	Average
1	5.5e-004	-2.5789e-005	2.3532e-004	1.0815e-005
2	1.1e-003	-8.7871e-005	1.3814e-003	7.8549e-005
3	1.65e-003	-2.7272e-004	4.3595e-003	3.0495e-004
4	2.2e-003	-9.1475e-004	1.014e-002	8.546e-004
5	2.75e-003	-2.3181e-003	1.9567e-002	1.947e-003
6	3.3e-003	-4.6e-003	3.3392e-002	3.8401e-003
7	3.85e-003	-7.5357e-003	5.2257e-002	6.8224e-003
8	4.4e-003	-1.0644e-002	7.6688e-002	1.1221e-002
9	4.95e-003	-1.3311e-002	0.10706	1.742e-002
10	5.5e-003	-1.4925e-002	0.14357	2.5871e-002
11	6.05e-003	-1.4916e-002	0.18628	3.7093e-002
12	6.6e-003	-1.2666e-002	0.23508	5.1646e-002
13	7.15e-003	-7.4157e-003	0.28972	7.0103e-002
14	7.7e-003	1.7862e-003	0.34976	9.3026e-002
15	8.25e-003	1.6047e-002	0.41455	0.12095
16	8.8e-003	3.6477e-002	0.48334	0.15438
17	9.35e-003	6.4064e-002	0.55527	0.19378
18	9.9e-003	9.9613e-002	0.62944	0.23958
19	1.045e-002	0.14377	0.70488	0.2921
20	1.1e-002	0.19711	0.78062	0.35158

Large Mass Method: 0.022s



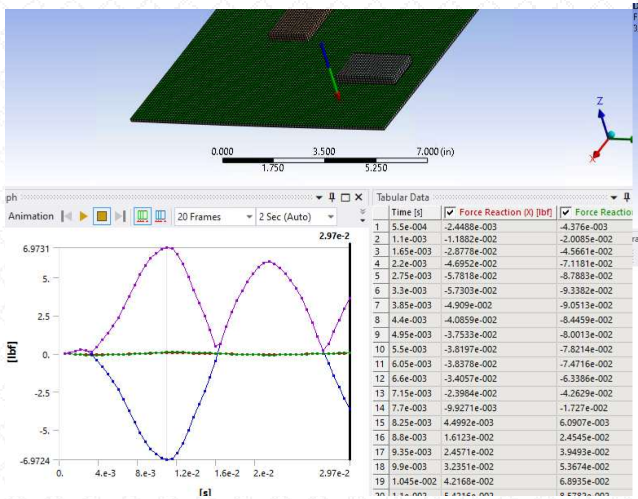
Tabular Data

	Time [s]	Minimum [in]	Maximum [in]	Average
1	5.5e-004	-2.6688e-005	2.3085e-004	1.3755e-005
2	1.1e-003	-8.6547e-005	1.3748e-003	9.9792e-005
3	1.65e-003	-3.0809e-004	4.3181e-003	3.867e-004
4	2.2e-003	-1.0451e-003	9.9023e-003	1.0812e-003
5	2.75e-003	-2.5808e-003	1.8904e-002	2.4575e-003
6	3.3e-003	-4.9307e-003	3.2016e-002	4.8393e-003
7	3.85e-003	-7.7394e-003	4.983e-002	8.5943e-003
8	4.4e-003	-1.0368e-002	7.2822e-002	1.4147e-002
9	4.95e-003	-1.2048e-002	0.10134	2.2e-002
10	5.5e-003	-1.2026e-002	0.13559	3.2739e-002
11	6.05e-003	-9.5351e-003	0.17566	4.7022e-002
12	6.6e-003	-3.7312e-003	0.22145	6.5539e-002
13	7.15e-003	6.4135e-003	0.27278	8.8974e-002
14	7.7e-003	2.2128e-002	0.32927	0.11798
15	8.25e-003	4.4706e-002	0.39046	0.15315
16	8.8e-003	7.5344e-002	0.45576	0.19503
17	9.35e-003	0.11503	0.52446	0.2441
18	9.9e-003	0.16452	0.5958	0.3007
19	1.045e-002	0.22439	0.66893	0.36507

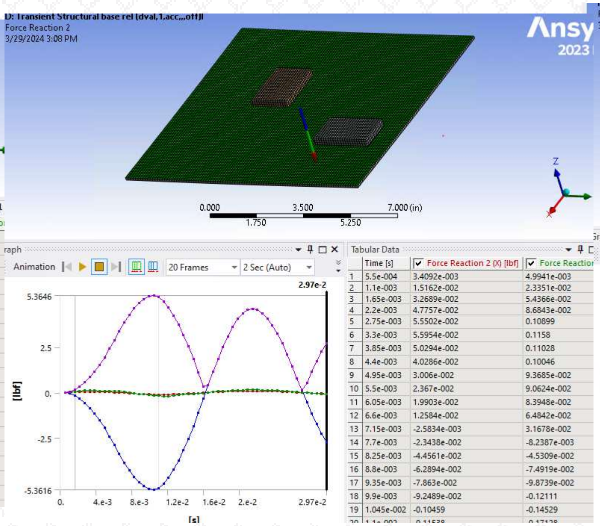
‘Base Excitation’ set to ‘Yes’.’Absolute Result’ set to ‘Yes’. Corrected Load): 0.022s

The Large Mass Method

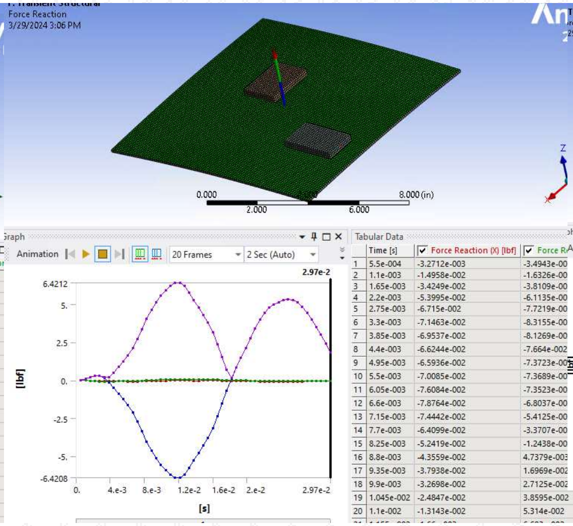
- The displacement results of the previous slide compariing the Large Mass Method to standard enforced motion (DVAL command) are close enough to consider the model (and methods) verified.
- However, let's go further and compare the reaction forces at the TTL components as was done in the previous blog post
- Recall, in that post we compared the reaction forces between a transient motion study ('Base Excitation' set to 'No') and a Response Spectrum solution
- Since this is the same model with the same loading, we don't expect those results to change now.
- In that study (transient response with 'Base Excitation' set to 'No'), we got a max response at component 1 of 6.973 lbf, and for component 2: 5.346 lbf



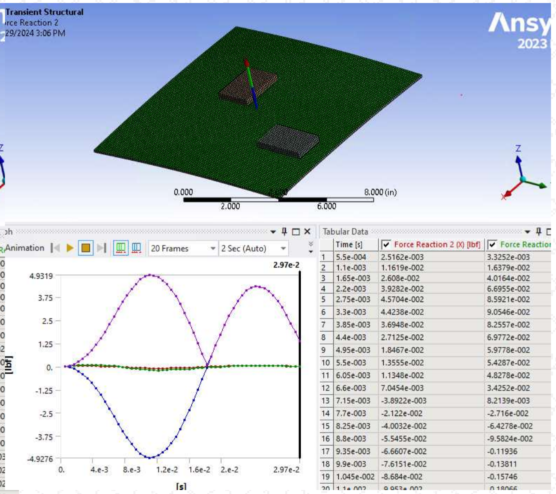
'Base Excitation' set to 'Yes'.'Absolute Result' set to 'Yes'. Component1 Max force = 6.973 lbf



'Base Excitation' set to 'Yes'.'Absolute Result' set to 'Yes'. Component2 Max force = 5.346 lbf



Large Mass Method. Component1 Max force = 6.421 lbf



Large Mass Method. Component2 Max force = 4.932 lbf

Conclusions

- The innocent looking ‘Acceleration’ load povides users with hidden possibilities when performing a transient structural analysis
- In our experience providing Ansys Technical Support, most users are unaware that the default setting (Base Excitation (No)) conceals the ability to apply enforced motion to a model and to view the results either in a ‘base-relative’ reference frame, or in ‘absolute’ (inertial) coordinates
- In this article, we’ve explored how users may access this functionality –and to check the results using the Large Mass Method
- In spite of an odd hiccup when defining the base excitation using a function with a deactivated regime (which shouldn’t occur with manually defined tabular loads), the functionaity works as advertized (using the equally obscure DVAL command for mode-superposition-based solutions. A discussion of this command was beyond the scope of this article)