# FEA Summary_2 Dynamic Analysis 

Ang Lee
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## Dynamic Analysis

The dynamic analysis will be carried out by 3 steps.

1) First step_The modal analysis for the APA frame itself. We want to understand the APA frame first before it is attached to the anything.
a) What is the mode shape and associated natural frequency.
b) How the constraint will effect its natural frequency.
c) The information will feed to the vendor for the purpose of the shock absorber (WRI) selection.
2) Second Step _ random vibration. Once first step is completed, a preliminary shock absorber is identified. We put it into FEA model to run the random vibration based on a given PSD curve.
3) Third step _ shock response. It is similar approach as step 2 but with different input data (ex 6.4 G over 11 ms half sine shock)

## Step 1 Modal Analysis APA Frame _FEA model (loading and boundary condition)



## APA Frame _Modal Analysis



Two models have be studied.

Model A: Assumed One M20 hole/each corner is constrained (yellow shaded).


## APA Frame _Modal Analysis

- Run static solution first (prestress).
- Then, run modal Analysis with prestress on.
- Search first 30 natural frequency up to $0-200 \mathrm{~Hz}$ range.
- Mass participation factor is extracted and exported to excel sheet for further evaluation.


## APA Frame _Modal Analysis _Model A



## RATIO EFF. MASS TO TOTAL MASS

| MODE | FREQUENCY <br> (HZ) | X | Y | Z |
| :---: | :---: | :---: | :---: | :---: |
| 1 | 11.7861 | 2.00E-09 | 4.01E-06 | 0.387169 |
| 2 | 16.6865 | $1.28 \mathrm{E}-07$ | $4.45 \mathrm{E}-01$ | 3.54E-08 |
| 3 | 16.9827 | $4.82 \mathrm{E}-09$ | $8.86352 \mathrm{E}-06$ | 4.82E-06 |
| 4 | 28.7198 | $3.44 \mathrm{E}-08$ | 3.03E-06 | $2.42 \mathrm{E}-01$ |
| 5 | 34.5217 | 3.16E-08 | 6.96E-06 | 0.0339109 |
| 6 | 38.8151 | 9.22E-06 | 9.01E-07 | $3.85 \mathrm{E}-02$ |
| 7 | 40.7882 | $3.80 \mathrm{E}-07$ | 4.97E-03 | 3.35E-05 |
| 8 | 41.4788 | $4.15 \mathrm{E}-07$ | $2.01 \mathrm{E}-07$ | 6.35E-06 |
| 9 | 45.1899 | 7.82E-05 | $3.99 \mathrm{E}-07$ | $6.54 \mathrm{E}-02$ |
| 10 | 50.7935 | 0.443764 | 6.50E-07 | $4.68 \mathrm{E}-06$ |
| 11 | 59.3438 | 6.61E-07 | $8.60 \mathrm{E}-06$ | $7.53 \mathrm{E}-03$ |
| 12 | 63.6246 | $2.27 \mathrm{E}-06$ | 2.17E-05 | $1.02 \mathrm{E}-02$ |
| 13 | 64.2536 | $3.35 \mathrm{E}-08$ | $1.78 \mathrm{E}-01$ | 3.92E-07 |
| 14 | 66.4298 | 7.05E-07 | $3.62 \mathrm{E}-08$ | 2.01E-08 |
| 15 | 78.1044 | $1.25 \mathrm{E}-07$ | $1.10 \mathrm{E}-01$ | $1.49 \mathrm{E}-07$ |
| 16 | 81.0604 | $5.13 \mathrm{E}-08$ | $1.70 \mathrm{E}-08$ | 7.05E-07 |
| 17 | 88.458 | $4.12 \mathrm{E}-07$ | $3.07 \mathrm{E}-07$ | $5.39 \mathrm{E}-02$ |
| 18 | 92.9942 | 2.37E-08 | $1.83 \mathrm{E}-07$ | $2.43 \mathrm{E}-03$ |
| 19 | 97.8719 | $3.67 \mathrm{E}-08$ | 0.164955 | 3.76E-07 |
| 20 | 109.005 | $2.28 \mathrm{E}-10$ | 6.81E-09 | 3.47E-02 |
| 21 | 114.115 | 3.93E-09 | 7.74E-04 | $1.21 \mathrm{E}-08$ |
| 22 | 117.425 | $2.58 \mathrm{E}-08$ | 6.55E-09 | $2.44 \mathrm{E}-07$ |
| 23 | 132.484 | $9.66 \mathrm{E}-08$ | 2.90E-09 | 6.96E-08 |
| 24 | 133.261 | $4.58 \mathrm{E}-08$ | $2.77 \mathrm{E}-08$ | $2.91 \mathrm{E}-07$ |
| 25 | 139.231 | $2.12 \mathrm{E}-08$ | $1.91 \mathrm{E}-08$ | $1.37 \mathrm{E}-02$ |
| 26 | 156.431 | 3.36E-07 | 3.86E-07 | $5.02 \mathrm{E}-08$ |
| 27 | 165.545 | 6.18E-07 | $2.42 \mathrm{E}-05$ | $6.82 \mathrm{E}-08$ |
| 28 | 165.731 | $7.75 \mathrm{E}-12$ | $1.65 \mathrm{E}-02$ | $6.06 \mathrm{E}-07$ |
| 29 | 169.65 | $9.34 \mathrm{E}-08$ | $4.15 \mathrm{E}-07$ | $2.63 \mathrm{E}-02$ |
| 30 | 185.552 | 7.58E-04 | $1.43 \mathrm{E}-08$ | $3.22 \mathrm{E}-06$ |
| ----- | -------------- | ------------------ | ------------------- | ------------ |
| sum |  | 0.444616 | 0.920486 | 0.915319 |

## APA Frame _Modal Analysis _Model A



Mode 2: $\mathrm{fn}=16.686 \mathrm{~Hz}$ (up/down).The mode shape is mostly parallel (in plane) to the frame.


RATIO EFF. MASS TO TOTAL MASS

| FREQUENCY (HZ) | X | Y | Z |
| :---: | :---: | :---: | :---: |
| 11.7861 | 2.00E-09 | 4.01E-06 | 0.387169 |
| 16.6865 | $1.28 \mathrm{E}-07$ | $4.45 \mathrm{E}-01$ | $3.54 \mathrm{E}-08$ |
| 16.9827 | $4.82 \mathrm{E}-09$ | $8.86352 \mathrm{E}-06$ | $4.82 \mathrm{E}-06$ |
| 28.7198 | $3.44 \mathrm{E}-08$ | 3.03E-06 | $2.42 \mathrm{E}-01$ |
| 34.5217 | $3.16 \mathrm{E}-08$ | 6.96E-06 | 0.0339109 |
| 38.8151 | $9.22 \mathrm{E}-06$ | 9.01E-07 | $3.85 \mathrm{E}-02$ |
| 40.7882 | $3.80 \mathrm{E}-07$ | 4.97E-03 | $3.35 \mathrm{E}-05$ |
| 41.4788 | $4.15 \mathrm{E}-07$ | 2.01E-07 | $6.35 \mathrm{E}-06$ |
| 45.1899 | 7.82E-05 | 3.99E-07 | $6.54 \mathrm{E}-02$ |
| 50.7935 | 0.443764 | 6.50E-07 | $4.68 \mathrm{E}-06$ |
| 59.3438 | $6.61 \mathrm{E}-07$ | 8.60E-06 | $7.53 \mathrm{E}-03$ |
| 63.6246 | 2.27E-06 | 2.17E-05 | $1.02 \mathrm{E}-02$ |
| 64.2536 | $3.35 \mathrm{E}-08$ | $1.78 \mathrm{E}-01$ | $3.92 \mathrm{E}-07$ |
| 66.4298 | 7.05E-07 | $3.62 \mathrm{E}-08$ | $2.01 \mathrm{E}-08$ |
| 78.1044 | $1.25 \mathrm{E}-07$ | $1.10 \mathrm{E}-01$ | $1.49 \mathrm{E}-07$ |
| 81.0604 | $5.13 \mathrm{E}-08$ | $1.70 \mathrm{E}-08$ | $7.05 \mathrm{E}-07$ |
| 88.458 | $4.12 \mathrm{E}-07$ | 3.07E-07 | $5.39 \mathrm{E}-02$ |
| 92.9942 | $2.37 \mathrm{E}-08$ | $1.83 \mathrm{E}-07$ | $2.43 \mathrm{E}-03$ |
| 97.8719 | $3.67 \mathrm{E}-08$ | 0.164955 | $3.76 \mathrm{E}-07$ |
| 109.005 | $2.28 \mathrm{E}-10$ | 6.81E-09 | $3.47 \mathrm{E}-02$ |
| 114.115 | 3.93E-09 | 7.74E-04 | $1.21 \mathrm{E}-08$ |
| 117.425 | $2.58 \mathrm{E}-08$ | 6.55E-09 | $2.44 \mathrm{E}-07$ |
| 132.484 | $9.66 \mathrm{E}-08$ | 2.90E-09 | $6.96 \mathrm{E}-08$ |
| 133.261 | $4.58 \mathrm{E}-08$ | $2.77 \mathrm{E}-08$ | $2.91 \mathrm{E}-07$ |
| 139.231 | $2.12 \mathrm{E}-08$ | $1.91 \mathrm{E}-08$ | $1.37 \mathrm{E}-02$ |
| 156.431 | $3.36 \mathrm{E}-07$ | 3.86E-07 | $5.02 \mathrm{E}-08$ |
| 165.545 | 6.18E-07 | 2.42E-05 | $6.82 \mathrm{E}-08$ |
| 165.731 | $7.75 \mathrm{E}-12$ | $1.65 \mathrm{E}-02$ | $6.06 \mathrm{E}-07$ |
| 169.65 | $9.34 \mathrm{E}-08$ | 4.15E-07 | $2.63 \mathrm{E}-02$ |
| 185.552 | 7.58E-04 | $1.43 \mathrm{E}-08$ | $3.22 \mathrm{E}-06$ |
| --------------- | ------------------- | ------------------- | -------------- |
|  | 0.444616 | 0.920486 | 0.915319 |

Mode $3 \mathrm{fn}=16.9827 \mathrm{~Hz}$. mode shape mostly is in twist motion.

## APA Frame _Modal Analysis _Model A

```
B:Modal
Otal Deformation-Mode 4-28.72 Hz
Type: Total Deformation
requency: 28.72 Hz
Unit: m
Max. .
Min:0
\square0.11428
-0.10158
-0.088886
-0.06349
-0.050792
-0.038094
-0.025396
0.012698
```



Mode 4 : fn=28.719 Hz (higher mode shape _short wave)


| RATIO EFF. MASS TO TOTAL MASS |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| MODE | FREQUENCY (HZ) | X | Y | Z |
| 1 | 11.7861 | 2.00E-09 | 4.01E-06 | 0.387169 |
| 2 | 16.6865 | $1.28 \mathrm{E}-07$ | $4.45 \mathrm{E}-01$ | $3.54 \mathrm{E}-08$ |
| 3 | 16.9827 | 4.82E-09 | $8.86352 \mathrm{E}-06$ | $4.82 \mathrm{E}-06$ |
| 4 | 28.7198 | $3.44 \mathrm{E}-08$ | 3.03E-06 | $2.42 \mathrm{E}-01$ |
| 5 | 34.5217 | $3.16 \mathrm{E}-08$ | 6.96E-06 | 0.0339109 |
| 6 | 38.8151 | 9.22E-06 | 9.01E-07 | $3.85 \mathrm{E}-02$ |
| 7 | 40.7882 | 3.80E-07 | 4.97E-03 | $3.35 \mathrm{E}-05$ |
| 8 | 41.4788 | $4.15 \mathrm{E}-07$ | 2.01E-07 | $6.35 \mathrm{E}-06$ |
| 9 | 45.1899 | 7.82E-05 | 3.99E-07 | $6.54 \mathrm{E}-02$ |
| 10 | 50.7935 | 0.443764 | 6.50E-07 | $4.68 \mathrm{E}-06$ |
| 11 | 59.3438 | 6.61E-07 | 8.60E-06 | $7.53 \mathrm{E}-03$ |
| 12 | 63.6246 | $2.27 \mathrm{E}-06$ | $2.17 \mathrm{E}-05$ | $1.02 \mathrm{E}-02$ |
| 13 | 64.2536 | $3.35 \mathrm{E}-08$ | $1.78 \mathrm{E}-01$ | $3.92 \mathrm{E}-07$ |
| 14 | 66.4298 | 7.05E-07 | $3.62 \mathrm{E}-08$ | $2.01 \mathrm{E}-08$ |
| 15 | 78.1044 | $1.25 \mathrm{E}-07$ | $1.10 \mathrm{E}-01$ | $1.49 \mathrm{E}-07$ |
| 16 | 81.0604 | 5.13E-08 | $1.70 \mathrm{E}-08$ | $7.05 \mathrm{E}-07$ |
| 17 | 88.458 | 4.12E-07 | 3.07E-07 | $5.39 \mathrm{E}-02$ |
| 18 | 92.9942 | $2.37 \mathrm{E}-08$ | $1.83 \mathrm{E}-07$ | $2.43 \mathrm{E}-03$ |
| 19 | 97.8719 | 3.67E-08 | 0.164955 | $3.76 \mathrm{E}-07$ |
| 20 | 109.005 | $2.28 \mathrm{E}-10$ | 6.81E-09 | $3.47 \mathrm{E}-02$ |
| 21 | 114.115 | 3.93E-09 | 7.74E-04 | $1.21 \mathrm{E}-08$ |
| 22 | 117.425 | 2.58E-08 | 6.55E-09 | $2.44 \mathrm{E}-07$ |
| 23 | 132.484 | 9.66E-08 | $2.90 \mathrm{E}-09$ | $6.96 \mathrm{E}-08$ |
| 24 | 133.261 | $4.58 \mathrm{E}-08$ | $2.77 \mathrm{E}-08$ | $2.91 \mathrm{E}-07$ |
| 25 | 139.231 | 2.12E-08 | $1.91 \mathrm{E}-08$ | $1.37 \mathrm{E}-02$ |
| 26 | 156.431 | 3.36E-07 | 3.86E-07 | $5.02 \mathrm{E}-08$ |
| 27 | 165.545 | 6.18E-07 | 2.42E-05 | $6.82 \mathrm{E}-08$ |
| 28 | 165.731 | $7.75 \mathrm{E}-12$ | $1.65 \mathrm{E}-02$ | $6.06 \mathrm{E}-07$ |
| 29 | 169.65 | $9.34 \mathrm{E}-08$ | 4.15E-07 | $2.63 \mathrm{E}-02$ |
| 30 | 185.552 | 7.58E-04 | $1.43 \mathrm{E}-08$ | 3.22E-06 |
| ----- | --------------- | ------------------- | ------------------ | ----------------- |
| sum |  | 0.444616 | 0.920486 | 0.915319 |

Mode 5 : $\mathrm{fn}=34.52 \mathrm{~Hz}$ (higher mode shape _short wave)

## APA Frame _Modal Analysis _Model B



> Mode $1 \mathrm{fn}=13.6 \mathrm{~Hz}$ (in/out) mode shape mostly is perpendicular to the frame

RATIO EFF. MASS TO TOTAL MASS

| MODE | FREQUENCY <br> (HZ) | X | Y | Z |
| :---: | :---: | :---: | :---: | :---: |
| 1 | 13.6087 | $1.64 \mathrm{E}-09$ | $1.12 \mathrm{E}-05$ | 0.498254 |
| 2 | 17.8591 | $2.34 \mathrm{E}-09$ | $1.07 \mathrm{E}-05$ | $4.06 \mathrm{E}-06$ |
| 3 | 18.1815 | 8.23E-08 | 0.494305 | 7.28E-06 |
| 4 | 35.2939 | $8.82 \mathrm{E}-11$ | 3.68E-06 | $1.23 \mathrm{E}-03$ |
| 5 | 39.5378 | 5.59E-06 | $2.66 \mathrm{E}-06$ | 0.114424 |
| 6 | 43.4486 | $1.21 \mathrm{E}-05$ | 5.82E-10 | $4.96 \mathrm{E}-02$ |
| 7 | 44.0168 | $6.95 \mathrm{E}-08$ | $3.47 \mathrm{E}-08$ | $1.89 \mathrm{E}-07$ |
| 8 | 44.4733 | $4.78 \mathrm{E}-07$ | $9.72 \mathrm{E}-05$ | $1.50 \mathrm{E}-05$ |
| 9 | 51.6591 | $1.07 \mathrm{E}-04$ | 5.17E-07 | $7.99 \mathrm{E}-02$ |
| 10 | 54.3444 | 0.423929 | 1.17E-07 | $2.02 \mathrm{E}-05$ |
| 11 | 60.7344 | $3.22 \mathrm{E}-07$ | $2.68 \mathrm{E}-06$ | $7.85 \mathrm{E}-03$ |
| 12 | 68.6011 | $9.03 \mathrm{E}-07$ | $9.29 \mathrm{E}-09$ | $3.23 \mathrm{E}-03$ |
| 13 | 79.9817 | $1.24 \mathrm{E}-07$ | $9.12 \mathrm{E}-02$ | $3.73 \mathrm{E}-08$ |
| 14 | 81.6695 | $1.66 \mathrm{E}-07$ | 8.47E-10 | $1.91 \mathrm{E}-07$ |
| 15 | 89.6974 | $4.30 \mathrm{E}-07$ | 7.38E-07 | $5.72 \mathrm{E}-02$ |
| 16 | 101.14 | $2.75 \mathrm{E}-09$ | $3.28 \mathrm{E}-08$ | 6.66E-04 |
| 17 | 115.598 | 5.76E-09 | $4.54 \mathrm{E}-05$ | $8.92 \mathrm{E}-08$ |
| 18 | 124.064 | $1.43 \mathrm{E}-07$ | 5.25E-07 | 7.65E-09 |
| 19 | 127.816 | $3.20 \mathrm{E}-08$ | 0.19272 | $2.06 \mathrm{E}-07$ |
| 20 | 132.011 | $3.49 \mathrm{E}-08$ | $1.39 \mathrm{E}-05$ | $2.84 \mathrm{E}-03$ |
| 21 | 136.503 | $5.81 \mathrm{E}-08$ | 2.61E-07 | $2.75 \mathrm{E}-08$ |
| 22 | 141.351 | $1.71 \mathrm{E}-08$ | $4.25 \mathrm{E}-08$ | $1.05 \mathrm{E}-02$ |
| 23 | 156.508 | 7.84E-07 | $1.08 \mathrm{E}-07$ | 8.05E-08 |
| 24 | 165.078 | $5.78 \mathrm{E}-10$ | $9.76 \mathrm{E}-03$ | $2.90 \mathrm{E}-08$ |
| 25 | 165.493 | $1.11 \mathrm{E}-08$ | $9.19 \mathrm{E}-06$ | $4.03 \mathrm{E}-06$ |
| 26 | 168.406 | $4.98 \mathrm{E}-07$ | $8.34 \mathrm{E}-08$ | $5.78 \mathrm{E}-08$ |
| 27 | 185.74 | $2.67 \mathrm{E}-04$ | $3.10 \mathrm{E}-05$ | $2.56 \mathrm{E}-05$ |
| 28 | 187.064 | $3.03 \mathrm{E}-06$ | $1.82 \mathrm{E}-03$ | $3.10 \mathrm{E}-02$ |
| 29 | 187.176 | 5.07E-07 | $1.57 \mathrm{E}-02$ | $3.72 \mathrm{E}-03$ |
| 30 | 188.864 | $1.21 \mathrm{E}-07$ | 3.51E-07 | $2.35 \mathrm{E}-05$ |
| ----- | -------------- | ------------------- | ------------------ | ------------------- |
| sum |  | 0.424329 | 0.805733 | 0.860588538 |
| ----- | --------------- | ------------------- | ------------------- | ------------------- |

## APA Frame _Modal Analysis _Model B



Mode $2 \mathrm{fn}=17.859 \mathrm{~Hz}$. mode shape mostly is in twist motion.


Mode 3: $\mathrm{fn}=18.1815 \mathrm{~Hz}$ (up/down).The mode shape is mostly parallel (in plane) to the frame.

## Additional case addl a support in the middlle



## APA Frame _Modal Analysis _Model B_1 (a middle is added)



Mode $1 \mathrm{fn}=34.49 \mathrm{~Hz}$ (in/out) mode shape is mostly perpendicular to the frame.

RATIO EFF. MASS TO TOTAL MASS

| MODE | FREQUENCY <br> (HZ) | X | Y | $Z$ |
| :---: | :---: | :---: | :---: | :---: |
| 1 | 34.4941 | 2.00E-09 | $4.33 \mathrm{E}-07$ | 0.365325 |
| 2 | 39.119 | $1.28 \mathrm{E}-07$ | $1.46 \mathrm{E}-07$ | $4.29 \mathrm{E}-02$ |
| 3 | 43.3248 | 4.82E-09 | $1.35 \mathrm{E}-08$ | 5.33E-02 |
| 4 | 53.1843 | $3.44 \mathrm{E}-08$ | $1.13 \mathrm{E}-05$ | $7.34 \mathrm{E}-03$ |
| 5 | 54.3884 | $3.16 \mathrm{E}-08$ | 1.58E-03 | $1.33525 \mathrm{E}-05$ |
| 6 | 54.4959 | 9.22E-06 | 0.165282 | $2.83 \mathrm{E}-06$ |
| 7 | 56.4894 | 3.80E-07 | $6.18 \mathrm{E}-08$ | $5.15 \mathrm{E}-12$ |
| 8 | 60.9898 | $4.15 \mathrm{E}-07$ | $6.32 \mathrm{E}-05$ | $1.75 \mathrm{E}-01$ |
| 9 | 63.0844 | 7.82E-05 | 0.340808 | $8.04 \mathrm{E}-05$ |
| 10 | 63.6207 | 0.443764 | $1.29 \mathrm{E}-05$ | $1.31 \mathrm{E}-06$ |
| 11 | 69.9498 | 6.61E-07 | $1.37 \mathrm{E}-05$ | $1.81 \mathrm{E}-02$ |
| 12 | 75.0834 | $2.27 \mathrm{E}-06$ | 8.18E-06 | $1.02 \mathrm{E}-01$ |
| 13 | 102.348 | 3.35E-08 | $3.55 \mathrm{E}-07$ | $4.07 \mathrm{E}-06$ |
| 14 | 121.39 | 7.05E-07 | $1.29 \mathrm{E}-02$ | $1.32 \mathrm{E}-08$ |
| 15 | 128.276 | $1.25 \mathrm{E}-07$ | 0.184317 | 7.81E-10 |
| 16 | 135.763 | 5.13E-08 | $3.41 \mathrm{E}-07$ | $4.02 \mathrm{E}-08$ |
| 17 | 138.414 | 4.12E-07 | $2.88 \mathrm{E}-03$ | $4.85 \mathrm{E}-06$ |
| 18 | 139.262 | 2.37E-08 | $4.24 \mathrm{E}-08$ | $5.22 \mathrm{E}-08$ |
| 19 | 139.661 | 3.67E-08 | $1.59 \mathrm{E}-06$ | $1.24 \mathrm{E}-02$ |
| 20 | 144.672 | $2.28 \mathrm{E}-10$ | $4.12 \mathrm{E}-09$ | $8.40 \mathrm{E}-05$ |
| 21 | 150.26 | 3.93E-09 | $1.88 \mathrm{E}-09$ | $5.39 \mathrm{E}-08$ |
| 22 | 156.099 | $2.58 \mathrm{E}-08$ | $4.56 \mathrm{E}-08$ | $1.46 \mathrm{E}-03$ |
| 23 | 166.475 | $9.66 \mathrm{E}-08$ | $4.41 \mathrm{E}-08$ | $2.35 \mathrm{E}-05$ |
| 24 | 173.972 | $4.58 \mathrm{E}-08$ | $7.41 \mathrm{E}-10$ | $2.23 \mathrm{E}-08$ |
| 25 | 179.024 | $2.12 \mathrm{E}-08$ | 6.38E-04 | $1.69 \mathrm{E}-10$ |
| 26 | 185.119 | 3.36E-07 | $1.94 \mathrm{E}-09$ | $2.82 \mathrm{E}-07$ |
| 27 | 187.07 | 6.18E-07 | 5.10E-07 | $2.42 \mathrm{E}-08$ |
| 28 | 191.029 | 7.75E-12 | 4.99E-08 | $9.96 \mathrm{E}-07$ |
| 29 | 194.768 | $9.34 \mathrm{E}-08$ | $1.55 \mathrm{E}-02$ | $4.78 \mathrm{E}-08$ |
| 30 | 196.555 | 7.58E-04 | $6.84 \mathrm{E}-07$ | $3.33 \mathrm{E}-02$ |
| ----- | -------------- | ------------------ |  | ------------------ |
| sum |  | 0.444616 | 0.723958 | 0.811361 |
| ----- | --------------- | ------------------- | ------------------ | -------------- |

## APA Frame _Modal Analysis _Model B_1 (a middle is added)



Mode 2: fn=39.12 Hz.


Mode $3 \mathrm{fn}=43.32 \mathrm{~Hz}$.

RATIO EFF. MASS TO TOTAL MASS

| MODE | FREQUENCY <br> (HZ) | X | Y | Z |
| :---: | :---: | :---: | :---: | :---: |
| 1 | 34.4941 | $2.00 \mathrm{E}-09$ | $4.33 \mathrm{E}-07$ | 0.365325 |
| 2 | 39.119 | $1.28 \mathrm{E}-07$ | $1.46 \mathrm{E}-07$ | $4.29 \mathrm{E}-02$ |
| 3 | 43.3248 | $4.82 \mathrm{E}-09$ | $1.35 \mathrm{E}-08$ | 5.33E-02 |
| 4 | 53.1843 | $3.44 \mathrm{E}-08$ | $1.13 \mathrm{E}-05$ | $7.34 \mathrm{E}-03$ |
| 5 | 54.3884 | $3.16 \mathrm{E}-08$ | $1.58 \mathrm{E}-03$ | $1.33525 \mathrm{E}-05$ |
| 6 | 54.4959 | $9.22 \mathrm{E}-06$ | 0.165282 | $2.83 \mathrm{E}-06$ |
| 7 | 56.4894 | $3.80 \mathrm{E}-07$ | $6.18 \mathrm{E}-08$ | $5.15 \mathrm{E}-12$ |
| 8 | 60.9898 | $4.15 \mathrm{E}-07$ | $6.32 \mathrm{E}-05$ | $1.75 \mathrm{E}-01$ |
| 9 | 63.0844 | $7.82 \mathrm{E}-05$ | 0.340808 | $8.04 \mathrm{E}-05$ |
| 10 | 63.6207 | 0.443764 | $1.29 \mathrm{E}-05$ | $1.31 \mathrm{E}-06$ |
| 11 | 69.9498 | $6.61 \mathrm{E}-07$ | $1.37 \mathrm{E}-05$ | $1.81 \mathrm{E}-02$ |
| 12 | 75.0834 | 2.27E-06 | 8.18E-06 | $1.02 \mathrm{E}-01$ |
| 13 | 102.348 | $3.35 \mathrm{E}-08$ | $3.55 \mathrm{E}-07$ | 4.07E-06 |
| 14 | 121.39 | 7.05E-07 | $1.29 \mathrm{E}-02$ | $1.32 \mathrm{E}-08$ |
| 15 | 128.276 | $1.25 \mathrm{E}-07$ | 0.184317 | $7.81 \mathrm{E}-10$ |
| 16 | 135.763 | 5.13E-08 | $3.41 \mathrm{E}-07$ | $4.02 \mathrm{E}-08$ |
| 17 | 138.414 | $4.12 \mathrm{E}-07$ | $2.88 \mathrm{E}-03$ | $4.85 \mathrm{E}-06$ |
| 18 | 139.262 | $2.37 \mathrm{E}-08$ | $4.24 \mathrm{E}-08$ | $5.22 \mathrm{E}-08$ |
| 19 | 139.661 | 3.67E-08 | $1.59 \mathrm{E}-06$ | $1.24 \mathrm{E}-02$ |
| 20 | 144.672 | $2.28 \mathrm{E}-10$ | $4.12 \mathrm{E}-09$ | $8.40 \mathrm{E}-05$ |
| 21 | 150.26 | $3.93 \mathrm{E}-09$ | $1.88 \mathrm{E}-09$ | $5.39 \mathrm{E}-08$ |
| 22 | 156.099 | $2.58 \mathrm{E}-08$ | $4.56 \mathrm{E}-08$ | $1.46 \mathrm{E}-03$ |
| 23 | 166.475 | $9.66 \mathrm{E}-08$ | $4.41 \mathrm{E}-08$ | $2.35 \mathrm{E}-05$ |
| 24 | 173.972 | $4.58 \mathrm{E}-08$ | $7.41 \mathrm{E}-10$ | $2.23 \mathrm{E}-08$ |
| 25 | 179.024 | $2.12 \mathrm{E}-08$ | $6.38 \mathrm{E}-04$ | $1.69 \mathrm{E}-10$ |
| 26 | 185.119 | $3.36 \mathrm{E}-07$ | $1.94 \mathrm{E}-09$ | $2.82 \mathrm{E}-07$ |
| 27 | 187.07 | $6.18 \mathrm{E}-07$ | $5.10 \mathrm{E}-07$ | $2.42 \mathrm{E}-08$ |
| 28 | 191.029 | $7.75 \mathrm{E}-12$ | $4.99 \mathrm{E}-08$ | $9.96 \mathrm{E}-07$ |
| 29 | 194.768 | $9.34 \mathrm{E}-08$ | $1.55 \mathrm{E}-02$ | $4.78 \mathrm{E}-08$ |
| 30 | 196.555 | 7.58E-04 | $6.84 \mathrm{E}-07$ | $3.33 \mathrm{E}-02$ |
| ----- | --------------- | ------------------ |  | ------------------- |
| sum |  | 0.444616 | 0.723958 | 0.811361 |
| ----- | --------------- | ------------------ | ------------------ | ------------------ |

## APA Frame _Modal Analysis



Two holes are constrained at each location.

One holes are constrained at each location.

## Modal Analysis

- That modal analysis information has been given to AVMR for their information to select the shock absorber.
- In the meantime, the consortium team have done some analytic analysis (Engineering note Appendix A) to pre-select a shock absorber such that FEA analysis can be moved forward for the random vibration and shock response.
- AVMR provided their report on June 6, 2020 as well, delays due to the COVID 19 issue.


## Step 2 Random Vibration

To access the dynamic response for whole assembly including APA shipping frame, WRI (wire rope isolator) and APA frame together is technically very challenged due to the limitation of the model size and time constraint. Therefore, an alternative approach is proposed to split the assembly into two models at the connection of the absorber:

- For the first model, the shipping frame, attenuator (inserted between 12 pairs absorber plates) and 2 APA frames (modeled as lump sum mass) are included. The PSD curve is applied at 3 locations at the shipping frame base (one is at the front and two are at the back).
- For the response of the APA frame, $2^{\text {nd }}$ model includes an APA frame, attenuator (inserted between 6 pairs absorber plates) and the attachment plate assembly. The PSD curve is directly applied at the one side of the absorber plates. The shipping frame stiffness in this case is considered as "infinite rigid" or part of the truck if you wish. The external dynamic disturbing directly goes to the base of the attenuator and passes to the APA frame. Any benefit of the vibration reduction (finite stiffness) or dumping from the shipping frame is not accounted for. Therefore, it is a conservative approach to access the APA frame dynamic response.

First model: Shipping frame +Attenuator + The APA (lump sum mass)


## Second model_APA frame + attachment plate assembly +

 Attenuator + absorber plateAssumed here is fixed boundary condition where PSD curve applied. Basically, it is assumed the shipping frame had "infinite rigid" stiffness, any external disturbance will be directly transmitted to WRI plate without considering any
Model
$5 / 11 / 2020$ I:05
vibration


WRI 16-350-08 attenuator is inserted here between the absorber plates.

## WRI data for M16-350-08

| PART NUMBER | DIMENSIONS in ( mm ) |  | ISOLATOR WEIGHT lbs (kg) | COMPRESSION |  |  | SHEAR/ROLL (AVG) |  |  | NOTES, FEATURES, MATERIALS/FINISHES |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | $\mathrm{H}_{ \pm .06}$ | $W_{\text {(reF) }}$ |  | Kv (VIBE) (lbs/in) | $\begin{gathered} \hline \mathrm{Ks}(\mathrm{SHOCK}) \\ (\mathrm{lbs} / \mathrm{in}) \end{gathered}$ |  | Kv (VIBE) (lbs/in) | Ks (SHOCK) (lbs/in) | $\begin{array}{\|c\|} \hline \text { MAX. } \\ \text { DEFLECT. (in) } \end{array}$ | NOTES: |
| M16-325-08-[ ] | $\begin{aligned} & 3.25 \\ & (82,6) \end{aligned}$ | $\begin{array}{\|c\|} 4.00 \\ (101.91 \end{array}$ | $3.71$ | 2486 | 1677 | 1.40 | 1287 | 977 | 1.40 | - ALL DIMENSIONS IN PARENTHESIS ARE METRIC (mm). <br> - SPECIALS AVAILABLE UPON REQUEST (MATERIALS, SIZE, |
| M16-350-08-[ ] | $\begin{aligned} & 3.50 \\ & (88,9) \end{aligned}$ | $\begin{gathered} 4.13 \\ (104,9) \end{gathered}$ | $\begin{aligned} & 3.73 \\ & (1.69) \end{aligned}$ | 2357 | 1496 | 1.65 | 719 | 818 | 1.65 | ADD $1.42 \mathrm{lbs}(.64 \mathrm{~kg})$ TO ISOLATOR WEIGHT FOR all-stainless steel versions. |
| M16-375-08-[] | 275 | 4.75 <br> $(120,7)$ | 4.10 | 1757 | 1044 | 1.90 | 502 | 534 | 1.90 | FEATURES: |
| M16-425-08-[ ] | $\begin{aligned} & 4.25 \\ & (108,0) \end{aligned}$ | $\underset{(133,4)}{5.25}$ | $\begin{aligned} & 4.60 \\ & (2.09) \end{aligned}$ | 1088 | 656 | 2.40 | 332 | 382 | 2.40 | - UNEQUALLED TEMP. RANGE: - $200^{\circ} \mathrm{F}$ TO $500^{\circ} \mathrm{F}$ <br> - three axis capability (6 DOF) |
| M16-490-08-[ ] | $\begin{aligned} & 4.90 \\ & (124,5) \end{aligned}$ | $\underset{(143,5)}{5.65}$ | $\begin{aligned} & 5.00 \\ & (2.27) \end{aligned}$ | 775 | 455 | 3.05 | 251 | 291 | 3.05 | - HIGH DAMPING: $\mathrm{C} / \mathrm{Cc} \approx .15-20$ <br> - LONG LIFE AND MAINTENANCE FREE |
| M16-540-08-[ ] | $\begin{aligned} & 5.40 \\ & (137,2) \end{aligned}$ | $\underset{(157,7)}{6.13}$ | $\underset{(2.46)}{5.42}$ | 550 | 346 | 3.55 | 173 | 236 | 3.55 | MATERIALS/FINISHES: <br> - CABLE: 300 SERIES SS PER MIL-W-83420 OR RR-W-410 |
| M16-610-08-[ ] | $\begin{gathered} 6.10 \\ (154,9) \end{gathered}$ | $\begin{aligned} & 7.10 \\ & (180,3) \end{aligned}$ | $\underset{(2.79)}{6.15}$ | 400 | 220 | 4.25 | 94 | 140 | 4.25 | - SCREWS: 300 SERIES SS PASSIVATED IAW ASTM A967 <br> - INSERTS: 300 SERIES SS (ALUM BARS ONLY) <br> - RETAINER BARS: SEE BELOW |

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## PSD Curve for the Air Ride Truck



Figure 9 - (Left) PSD of empty air ride trailer for each speed interval; (Right) PSD of loaded ( $21,000 \mathrm{~kg}$ ) air ride trailer for each speed interval. "Design Report for the DUNE APA shipping frames _ dynamic section"

## PSD Curve for ASTM D4169



## PSD Curve Comparison

1) The comparison of PSD curve shows that there are several magnitude difference between Air Ride and without Air Ride. It seems very effectively to reduce $\mathrm{G}^{\wedge} 2 / \mathrm{Hz}$ around the frequency range of $10-70 \mathrm{~Hz}$ where mostly APA and its lifting frame is oscillated at its natural frequency.
2) Therefore, the truck air ride is highly recommended to reduce the stress and any other complication (wire tension loosening or ...)

PSD Curve


## Radom Vibration



- The model is run as 3 steps:
- a) Static as prestress.
- b) Follow by Modal analysis.
- c) Follow by Random Vibration with PSD for Truck with air suspension.



## Radom Vibration_ $1^{\text {st }}$ step Static deflection (mm) with WRI

## B: Static Structural_1

Y Axis - Directional Deformation - End Time
Type: Directional Deformation(Y Axis)
Unit: mm
Global Coordinate System
Time: 1
Custom
Max: 0.0033037
Min: - 15.662
5/11/2020 11:48 AM
0.0033037
$-1.7373$
-3.4779
-5.2185
-6.9591
-8.6998
-10.44

- 12.181
-13.922
-15.662



## Static deflection (mm) just the main frame

## B: Static Structural_1 <br> Y Axis - Directional Deformation - End Time 3 <br> Type: Directional Deformation(Y Axis) <br> Unit: mm <br> Global Coordinate System <br> Time: 1 <br> Custom <br> Max: 0.0033037 <br> Min: - 1.1516 <br> 5/11/2020 11:54 AM <br> 

## Stress (MPa) due to the static solution



## Modal analysi <br> S <br> second step

| Mode | Frequency Hz |
| :---: | :---: |
| 1 | 2.2016 |
| 2 | 4.1377 |
| 3 | 4.1561 |
| 4 | 4.188 |
| 5 | 4.2358 |
| 6 | 5.8355 |
| 7 | 6.2275 |
| 8 | 6.8079 |
| 9 | 7.4476 |
| 10 | 9.4755 |
| 11 | 9.6137 |
| 12 | 9.7135 |
| 13 | 10.817 |
| 14 | 13.405 |
| 15 | 14.338 |
| 16 | 14.992 |
| 17 | 16.446 |
| 18 | 16.62 |
| 19 | 18.449 |
| 20 | 18.936 |
| 21 | 22.089 |
| 22 | 22.301 |
| 23 | 22.97 |
| 24 | 24.685 |
| 25 | 25.443 |
| 26 | 26.243 |
| 27 | 27.469 |
| 28 | 27.947 |
| 29 | 30.305 |
| 30 | 31.856 |
|  |  |
|  |  |


| 31 | 33.756 |
| :---: | :---: |
| 32 | 34.464 |
| 33 | 35.004 |
| 34 | 36.404 |
| 35 | 37.401 |
| 36 | 38.062 |
| 37 | 38.512 |
| 38 | 40.547 |
| 39 | 40.583 |
| 40 | 42.997 |
| 41 | 43.941 |
| 42 | 44.845 |
| 43 | 47.223 |
| 44 | 49.983 |
| 45 | 51.337 |
| 46 | 51.504 |
| 47 | 54.271 |
| 48 | 54.671 |
| 49 | 55.134 |
| 50 | 55.912 |
| 51 | 56.13 |
| 52 | 56.47 |
| 53 | 57.209 |
| 54 | 59.939 |
| 55 | 64.065 |
| 56 | 64.724 |
| 57 | 65.144 |
| 58 | 66.618 |
| 59 | 68.052 |
| 60 | 68.33 |


| 61 | 69.638 |
| :---: | :---: |
| 62 | 69.673 |
| 63 | 71.359 |
| 64 | 74.582 |
| 65 | 74.774 |
| 66 | 76.664 |
| 67 | 77.446 |
| 68 | 78.045 |
| 69 | 78.243 |
| 70 | 79.303 |
| 71 | 82.547 |
| 72 | 82.886 |
| 73 | 83.788 |
| 74 | 84.188 |
| 75 | 84.995 |
| 76 | 87.126 |
| 77 | 87.194 |
| 78 | 87.69 |
| 79 | 89.182 |
| 80 | 91.564 |
| 81 | 92.188 |
| 82 | 93.07 |
| 83 | 95.02 |
| 84 | 95.315 |
| 85 | 97.431 |
| 86 | 97.786 |
| 87 | 98.137 |
| 88 | 99.029 |
| 89 | 101.45 |
| 90 | 102.01 |
| 91 | 103.18 |
| 92 | 105.38 |
| 93 | 106.57 |
| 94 | 107.76 |
| 95 | 109.06 |
| 96 | 109.64 |
| 97 | 110.78 |
| 98 | 111.46 |
| 99 | 112.91 |
| 100 | 113.52 |
|  |  |
|  |  |
| 7 |  |
|  |  |
|  |  |

## Modal Analysis



2

## Modal Analysis_it is mostly due to WRI (fn=~4.2 Hz)



2

## For the shipping frame up/down $\rightarrow$ fn $=\sim 33.756 \mathrm{~Hz}$

## C: Modal

Total Deformation - Mode $31-33.756 \mathrm{~Hz}$
Type: Total Deformation
Frequency: 33.756 Hz

Unit: mm
Max: 2.2405
Min: 0
5/11/2020 12:04 PM

```
2.2405
1.9915
1.7426
1.4936
1.2447
0.99576
0.74682
0.49788
0.24894
0
```

The mode shape of $31^{\text {st }} \mathrm{fn}=33.76 \mathrm{~Hz}$ for the frame itself


## Ratio effective mass to total mass

RATIO EFF. MASS TO TOTAL MASS

| MODE | FREQUENCY | X | Y | Z |
| :---: | :---: | :---: | :---: | :---: |
| 1 | 2.20158 | $5.74 \mathrm{E}-06$ | $6.81 \mathrm{E}-06$ | 0.687517 |
| 2 | 4.13772 | 0.208913 | 0.392332 | $1.57 \mathrm{E}-03$ |
| 3 | 4.15607 | 0.330241 | 0.226638 | $1.03 \mathrm{E}-05$ |
| 4 | 4.18797 | $9.96 \mathrm{E}-02$ | $2.50 \mathrm{E}-05$ | $8.40 \mathrm{E}-03$ |
| 5 | 4.23582 | $6.49 \mathrm{E}-03$ | $2.37 \mathrm{E}-02$ | $3.45 \mathrm{E}-02$ |
| 6 | 5.83547 | $2.94 \mathrm{E}-05$ | $1.98 \mathrm{E}-05$ | $3.96 \mathrm{E}-02$ |
| 7 | 6.22748 | $1.43 \mathrm{E}-05$ | $3.16 \mathrm{E}-05$ | $7.71 \mathrm{E}-02$ |
| 8 | 6.80786 | $9.68 \mathrm{E}-06$ | $1.71 \mathrm{E}-04$ | $3.57 \mathrm{E}-03$ |
| 9 | 7.44758 | $3.17 \mathrm{E}-06$ | $3.59 \mathrm{E}-07$ | $4.10 \mathrm{E}-02$ |
| 10 | 9.47548 | $9.26 \mathrm{E}-06$ | $6.00 \mathrm{E}-04$ | $7.88 \mathrm{E}-05$ |
| 11 | 9.61371 | $3.21 \mathrm{E}-06$ | $4.06 \mathrm{E}-05$ | $7.45 \mathrm{E}-03$ |
| 12 | 9.71351 | $9.39 \mathrm{E}-08$ | $8.16 \mathrm{E}-06$ | $4.11 \mathrm{E}-06$ |
| 13 | 10.8171 | $7.42 \mathrm{E}-07$ | $5.53 \mathrm{E}-05$ | $1.30 \mathrm{E}-02$ |
| 14 | 13.405 | $1.40 \mathrm{E}-05$ | $2.80 \mathrm{E}-04$ | $9.22 \mathrm{E}-03$ |
| 15 | 14.3383 | $7.56 \mathrm{E}-06$ | $9.84 \mathrm{E}-04$ | $8.08 \mathrm{E}-04$ |
| 16 | 14.9916 | $2.24 \mathrm{E}-04$ | $9.41 \mathrm{E}-06$ | $4.64 \mathrm{E}-05$ |
| 17 | 16.446 | $5.23 \mathrm{E}-06$ | $6.99 \mathrm{E}-07$ | $7.03 \mathrm{E}-04$ |
| 18 | 16.6204 | $3.65 \mathrm{E}-06$ | $6.83 \mathrm{E}-07$ | $1.67 \mathrm{E}-04$ |
| 19 | 18.4486 | $2.92 \mathrm{E}-08$ | $1.77 \mathrm{E}-08$ | $3.22 \mathrm{E}-03$ |
| 20 | 18.9357 | $8.34 \mathrm{E}-07$ | $2.01 \mathrm{E}-06$ | $1.03 \mathrm{E}-04$ |
| 21 | 22.0893 | $1.03 \mathrm{E}-06$ | $3.81 \mathrm{E}-09$ | $2.04 \mathrm{E}-03$ |
| 22 | 22.3015 | $1.96 \mathrm{E}-06$ | $1.28 \mathrm{E}-06$ | $2.55 \mathrm{E}-03$ |
| 23 | 22.9698 | $2.79 \mathrm{E}-02$ | $2.82 \mathrm{E}-04$ | $1.53 \mathrm{E}-10$ |
| 24 | 24.6852 | $2.16 \mathrm{E}-05$ | $1.63 \mathrm{E}-04$ | $1.63 \mathrm{E}-03$ |
| 25 | 25.4425 | $3.60 \mathrm{E}-06$ | $6.95 \mathrm{E}-07$ | $1.07 \mathrm{E}-04$ |
| 26 | 26.2425 | $8.67 \mathrm{E}-05$ | $1.46 \mathrm{E}-02$ | $1.18 \mathrm{E}-05$ |
| 27 | 27.4686 | $4.97 \mathrm{E}-06$ | $8.12 \mathrm{E}-06$ | $6.92 \mathrm{E}-04$ |
| 28 | 27.9465 | $4.91 \mathrm{E}-06$ | $2.24 \mathrm{E}-05$ | $4.01 \mathrm{E}-04$ |
| 29 | 30.3051 | $6.68 \mathrm{E}-07$ | $2.69 \mathrm{E}-05$ | $1.35 \mathrm{E}-05$ |
| 30 | 31.8563 | $2.97 \mathrm{E}-05$ | $6.34 \mathrm{E}-05$ | $5.20 \mathrm{E}-04$ |
|  |  |  |  |  |

33.7563
34.4635 35.0038 36.4041 37.4008 38.0616 38.512 40.5474 40.583 42.9965 43.9406 44.8451 47.2229 49.9831 51.3371 51.5035 54.2711 54.6713 55.1335 55.9117 56.1296 56.47 57.2089 59.9386 64.0653 64.7241 65.1443 66.6177 68.0519 68.3304 69.6381 69.6725 71.3591 74.5817 74.7744 76.6636 77.4458 78.0453 78.2433 79.3032 82.547 82.8865 83.7884 84.1881 84.9949

| 76 | 87.1263 | 1.57E-05 | 5.81E-05 | 8.96E-05 |
| :---: | :---: | :---: | :---: | :---: |
| 77 | 87.1938 | 2.54E-04 | 2.18E-04 | 2.11E-04 |
| 78 | 87.6903 | 1.96E-03 | 3.07E-03 | 2.99E-06 |
| 79 | 89.1823 | 5.38E-03 | 1.55E-05 | 7.41E-07 |
| 80 | 91.5636 | 5.33E-05 | 4.05E-07 | 3.34E-05 |
| 81 | 92.1883 | $2.74 \mathrm{E}-03$ | 1.09E-03 | 8.31E-08 |
| 82 | 93.0705 | 6.37E-05 | 8.98E-05 | 9.35E-05 |
| 83 | 95.0196 | 3.23E-03 | 3.11E-03 | 2.54E-05 |
| 84 | 95.3154 | 5.83E-05 | 1.04E-04 | 8.82E-04 |
| 85 | 97.431 | $5.71 \mathrm{E}-10$ | 7.10E-05 | 6.56E-08 |
| 86 | 97.7859 | 1.56E-03 | 8.94E-06 | $2.58 \mathrm{E}-06$ |
| 87 | 98.1365 | 3.06E-05 | 4.15E-06 | 2.18E-04 |
| 88 | 99.0289 | 2.81E-04 | 9.01E-06 | 6.28E-07 |
| 89 | 101.453 | 5.27E-03 | 3.99E-05 | 1.69E-06 |
| 90 | 102.009 | 8.10E-05 | 2.60E-05 | $1.89 \mathrm{E}-06$ |
| 91 | 103.18 | 9.89E-05 | 9.92E-05 | 6.99E-05 |
| 92 | 105.378 | 8.12E-09 | 1.33E-06 | 1.36E-04 |
| 93 | 106.572 | 1.16E-03 | 2.19E-03 | 1.00E-06 |
| 94 | 107.761 | 1.59E-05 | 3.01E-05 | 2.14E-06 |
| 95 | 109.062 | 2.79E-06 | 2.20E-05 | 5.52E-05 |
| 96 | 109.643 | 1.02E-05 | 1.66E-08 | 4.28E-05 |
| 97 | 110.781 | 5.31E-04 | 1.34E-07 | 2.87E-05 |
| 98 | 111.462 | 2.87E-03 | 2.28E-04 | 4.44E-05 |
| 99 | 112.91 | 4.19E-04 | 7.85E-05 | 7.12E-05 |
| 100 | 113.518 | 9.52E-04 | 3.31E-04 | $3.23 \mathrm{E}-05$ |
|  |  |  |  |  |
| sum |  | 0.898971 | 0.90079 | 0.945102 |

The stress (MPa) from the random vibrations (1 sigma).


The stress (MPa) from the random vibrations (3 sigma).


The combined stress (MPa) from the static + random vibrations (3 sigma).


S355 steel has a minimum yield strength of 355 MPa and 475 MPa for its ultimate strength.

## Second model_APA frame + Attenuator + the Absorber plate

Assumed here is fixed boundary condition where PSD curve applied. Basically, it is assumed the shipping frame had "infinite rigid " stiffness, any external road disturbance will be directly transmitted to the WRI plate without counting any
Model
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$7: 05$
red


## APA frame random Vibration _ load step 1_static solution



## APA frame random Vibration _ deflection due to the static load

K: Copy of top and bot spring
Y Axis - Directional Deformation - 1. s
Type: Directional Deformation(Y Axis)
Unit: mm
Global Coordinate System
Time: 1 $\quad$ APA frame deflection $Y(\mathrm{~mm})$ vertical direction
Time: 1
Custom
Max: 7.4589e-6
Min: - 10.674
5/15/2020 10:10 AM

| $\square$ |
| :--- |
| $\square$ |
| - |
| - |
| $-1.4589 e-6$ |
| -2.3719 |
| -3.5579 |
| -4.7438 |
| -5.9298 |
| - |
| - |
| - |
| -8.1158 |
| -8.3017 |
| -9.4877 |
| -10.674 |


: Copy of top and bot spring



$-9.4877$
$-10.674$

## Load step 1_APA frame stress due to the static load



APA frame stress (MPa) due to the static load _ prestress

## Load step 2 _modal analysis result

Load step 2: Modal Analysis first several mode shapes are mostly from WRI (attenuator) _ low frequency ( $4-6 \mathrm{~Hz}$ )


## Load step 2 _ modal analysis



Mode 919.875 Hz


Mode 10 _21.5 Hz

## Ratio effective mass to total mass



The stress (MPa) from the random vibrations (3 sigma).


## The APA frame deflection due to the random vibration



## The total deflection Y (mm) (Up/down) due to static + random vibration (3 Sigma).



The clearance in UP/down is $58.5 \mathrm{~mm} /-59.2 \mathrm{~mm}>35 \mathrm{~mm}$ _OK

## The APA frame deflection (static + random vibration _3 sigma)

##  <br> With the air ride, 35 mm < $58.5 \mathrm{~mm} /-59.2$ mm clearance, OK. <br> 



With the ASTM 4169 truck ride, $58 \mathrm{~mm} \stackrel{\circ}{=} 58.5$ $\mathrm{mm} /-59.2 \mathrm{~mm}$ too close _ Not acceptable

## APA frame stress (3 Sigma) comparison due to the random vibration

 between ASTM 4169 and the air ride truck.


## The total deflection $\mathrm{X}(\mathrm{mm})$ _ longitudinal direction due to static + random vibration (3 Sigma).



The clearance in the longitudinal direction X $59 \mathrm{~mm} \gg 3 \mathrm{~mm}$

The total deflection Z (mm) _ the sideway direction due to static + random vibration (3 Sigma).


## Conclusion/Discussion

- The shipping frame is deflected about 1.2 mm statically (3 support points). Compared with its length of $\sim 6700 \mathrm{~mm}$, it is a very stiff structure as expected.
- The stress is well below 355 MPa yield strength for S355 steel.
- The random vibration result shows that the maximum stress is around 92 MPa (Peak) as shown in Figure 11. This 92 MPa is a fictitious number (stress concentration) without any physical mean. Without considering that, the stress should be around < 70 (MPa) for 1 Sigma ( $67 \%$ ) or 210 MPa for 3 Sigma ( $99.7 \%$ ) respectively. It is still below yield strength of 355 MPa . Even the stress from the static solution is included.
- A similar calculation is performed for APA frame in the second part of the calculation. The stress of APA frame due to the random vibration is around 29 MPa ( 1 sigma) as its peak value. Without considering its peak value, the actual stress should less < 20 MPa for 1 sigma and < 60 MPa for 3 Sigma as shown.
- The SS304 material has a minimum yield strength of 205 MPa and 515 MPa for its ultimate strength. The stress due to the random vibration for APA frame considered to be secondary for a truck with the air spring.
- The total deflection of APA is estimated by combining the static and random vibration. This $\sim 34 \mathrm{~mm}$ is well within the up/down clearance of $+58.5 /-86.2 \mathrm{~mm}$. The other 2 directions are within $\sim 3 \mathrm{~mm}$ envelope. The deflection result (UX, UY and UZ) is also extracted along the APA tubing side for a further processing at PSL to understand the wire stretching and stress.
- The results are summarized in Table 2. Additional stress plots are attached in Appendix C.


## Random Vibration result

Table 2 - Summary of the results for the random vibration analysis.
$\left.\begin{array}{|c|c|c|l|}\hline \text { Shipping frame stress (MPa) due to the random } \\ \text { vibration }\end{array} \quad<\mathbf{1 0}\right)$

## 3. Shock Response

- The shock response follows a similar approach as the random vibration except the last step which is RS (Response Spectrum) approach as recommended by Kelly Morgan, "Shock \& Vibration ANSYS Mechanical", April 27, 2015 for the large structure.
- A half sine wave is used for the shock load of 6.4 G over 11 ms

NNSYS Methods for Shock Analysis

## Response Spectrum Method <br> - Commonly used for large models

- Solve much faster than a full transient analvsis
- includes non-stationary excitations
- Linear analysis only


## Transient (Time History Analysis)

- Include non-stationa y and non-linear analysis
- Computationally quite expensive

MNSY Converting Time domain load into Spectrum ir put

Time domain data can be converted into Spectrum data (Freq domain) through RESP command in ANSYS:


Time domain data (Transient analysis)



Frequency domain data (Response Spectrum)

44 © 2011 ANSYS, Inc. April 27,2015

## Ansys tech support provides a transcript to convert from the time domain to the frequency domain (RESP)



| On Road (5000 $\mathbf{k m}$ ) <br> Terminal Peak Sawtooth <br> Puse duration: 11 ms |  |
| :---: | :---: |
| Amplitude [G-Pk] | Number of shocks |
| 5.1 | 42 |
| 6.4 | 21 |
| 7.6 | 3 |

## 3. Shock response




Shock response approach in ANSYS.

## 3. Shipping frame shock response

 MPa

Stress of the shipping frame due to the shock load (away from the stress concentration area).

## Shipping frame shock response



## Shipping frame deflection $\mathrm{Y}(\mathrm{mm})$ due to the shock load

C: Response Spectrum
Directional Deformation 2
Type: Directional Deformation(Y Axis)
Unit: mm
Solution Coordinate System
Time: 0
Custom
Max: 2.2416
Min: 0
6/8/2020 11:04 AM

| 2.2416 |
| :---: |
| 1.9925 |
| 1.7435 <br> 1.4944 |
| 1.4944 1.2453 |
| 0.99626 |
| 0.74719 |
| 0.49813 |
| 0.24906 |
| 0 |



The deflection Y (mm) due to the shock load.

## Combined stress(static + shock)

 response.

## The APA frame shock load



## The APA frame stress due to the shock loading





SS 304 Material
Syield=205 MPa minimum Su=515 MPa mininimum

## The APA frame displacement due to the shock loading



## The APA frame combined defection in Y(mm)




Total displacement $Y(\mathrm{~mm})$ due to the shock + static. This 13.6 mm << the clearance of $58.5 \mathrm{~mm} /-59.2 \mathrm{~mm}$ (Up/Down)

## The APA frame combined defection in X (mm)



Total displacement $X$ (mm) due to the shock + static. This 0.66 mm << the clearance of 59 mm .

## The APA frame combined defection in Z (mm)



Total displacement $Z(\mathrm{~mm})$ due to the shock + static. This number of 1.17 mm << 59 mm (clearance)

## Summery of shock response/conclusion

- The maximum stress of the shipping frame is 243 MPa (Peak). Without considering the peak stress (fictitious), the real stress is around < 170 MPa . S355 steel has a yield strength of 355 MPa and 475 MPa for its ultimate.
- The vertical deflection shipping is around $2.3 \mathrm{~mm}(\mathrm{Y})$ due to the shock load.
- Since maximum stress occurs at the middle of two end support, it is suggested that the additional support could be placed in the middle.
- The combined stress of static + shock response shows that maximum stress of the shipping frame is < 270 MPa which is still below 355 MPa .
- The APA frame stress due to the shock loading is 16.5 MPa . The combined stress of static + shock is 62 MPa . Both are well below the yield stress of 205 MPa for SS 304.
- The APA frame combined deflection (static + shock load) is $<14 \mathrm{~mm}$ in the vertical direction $\mathrm{Y} \ll$ well below the clearance of $+58.5 \mathrm{~mm} /-59.2 \mathrm{~mm}$. Other two directions are within an envelope of $\sim 1 \mathrm{~mm} \ll$ the clearance of 59 mm .
- Both APA shipping frame and APA frame are adequate for the additional dynamic load during the transportation. The truck with air spring is highly recommended.


## Additional slides

