KAGRA-SAS Note
Frame tower B1 and B2
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Abstract

This note contains descriptions, and analysis of the external frames of tower B1 and B2.
This note is organized in three sections. The first section is an introduction that describes the frame structure. The second section contains a finite element analysis (Fea) to verify the rigidity and natural frequencies on the frames. The third section is dedicated to the harmonic response analysis. Conclusions are reported in the section four.

1.1 Model description

The frames of the tower B1 and B2 are structure made by L profiles bolted to an upper and lower skirt. A cover plate is bolted to the frame structure at the top.

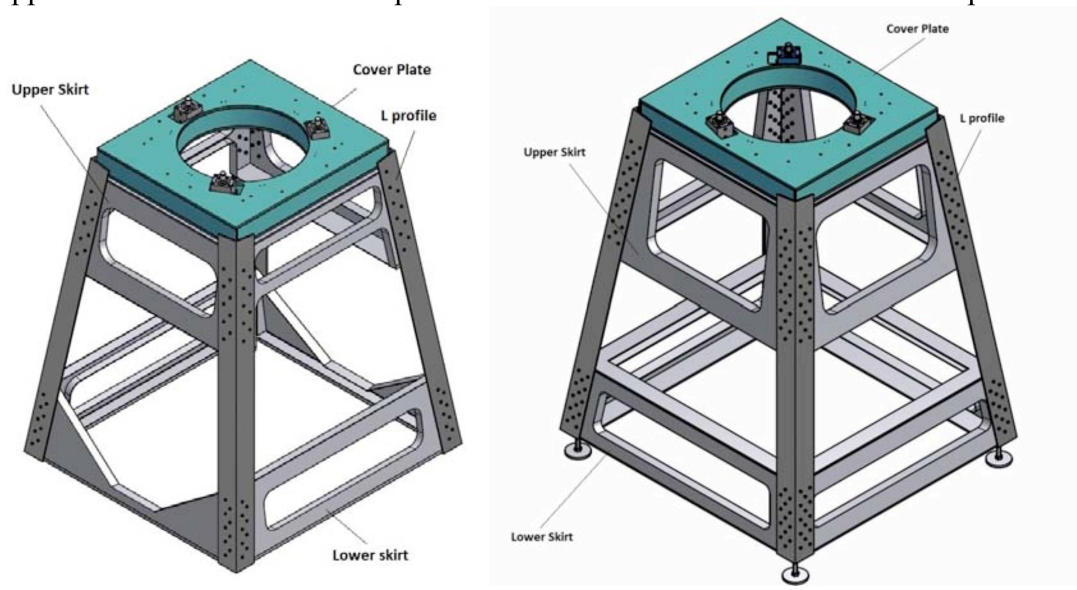


Fig.1

The four legs are made with L profiles that have a size 200x200x16mm, the plate of the structures have thickness ranging from 15 to 5mm. The entire structure is made of construction steel (S235JR).

The different colors of the model shown in figure 2 are associated to the different thickness. The cover plate is modeled as a single solid unit of assigned density to acquire the correct mass.

This is allowable because the cover plate, a welded structure, has his fundamental frequencies much higher than the structure here considered.

Fig. 2 Finite Element Analysis model

On the cover plate a lumped mass of 650Kg is added to take in account the load that is supported by the frame. Three models are analyzed with different constraints. The first model is constrained to the ground at the four corner of the lower skirt plate; the second one is constrained to the ground through four threaded rod risers designed to adjust the vertical positioning of the structure, in the third one, the entire lower plate of the skirt is constrained to the ground. In the actual implementation, the frames will be connected to the ground with threaded rods and nuts. The frames B1 have four threaded rods connected to a magnetic base anchored to a steel plate (see Fig.3) while frame B2 have threaded rods anchored to a concrete floor (see Fig.4). To calculate the worst possible case, in both cases in the simulation we considered a threaded rod M30 of 100 mm free length between nuts.

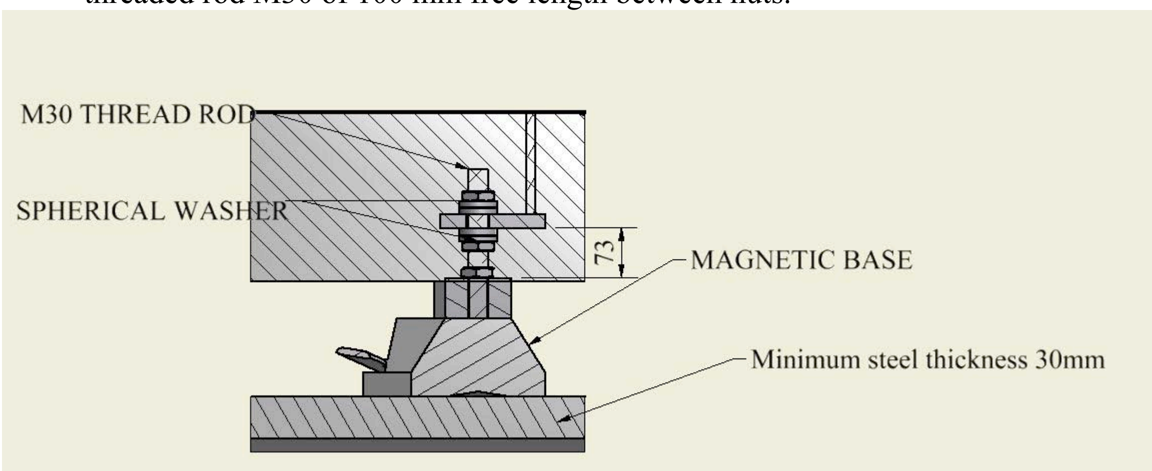


Fig.3

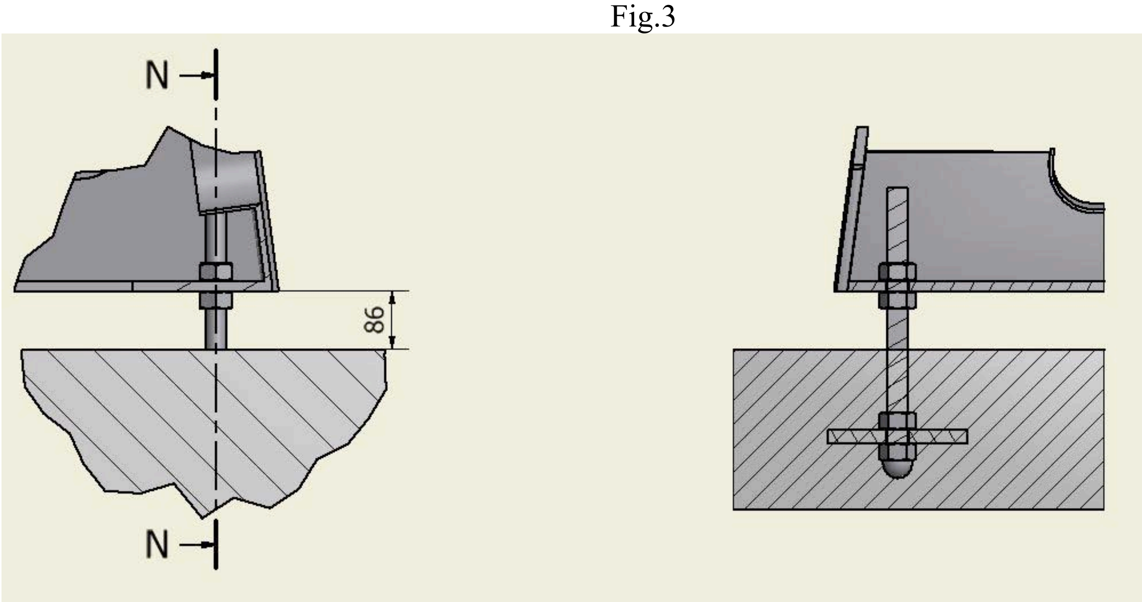
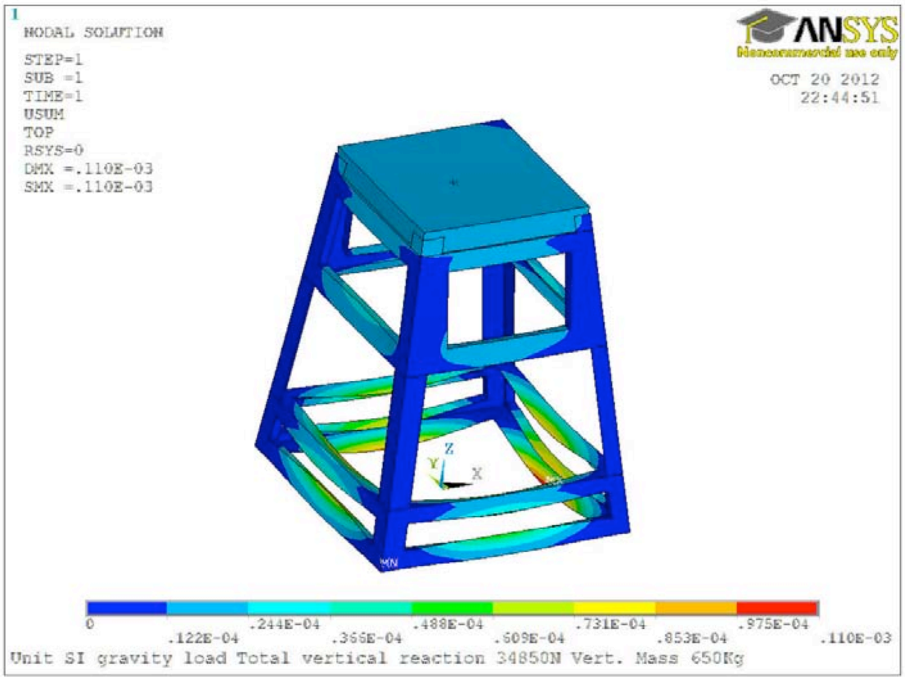


Fig.4

2.1 Static and modal analyses

The static analysis shows in both cases that the total static displacements under the gravitational load, are 0.11 mm for type B1 and 0.17mm for type B2. The total vertical reaction is 34850Newton (seeFig.5). The frame structure vertically has a good stiffens considering his overall dimension of about 2.2 meter.



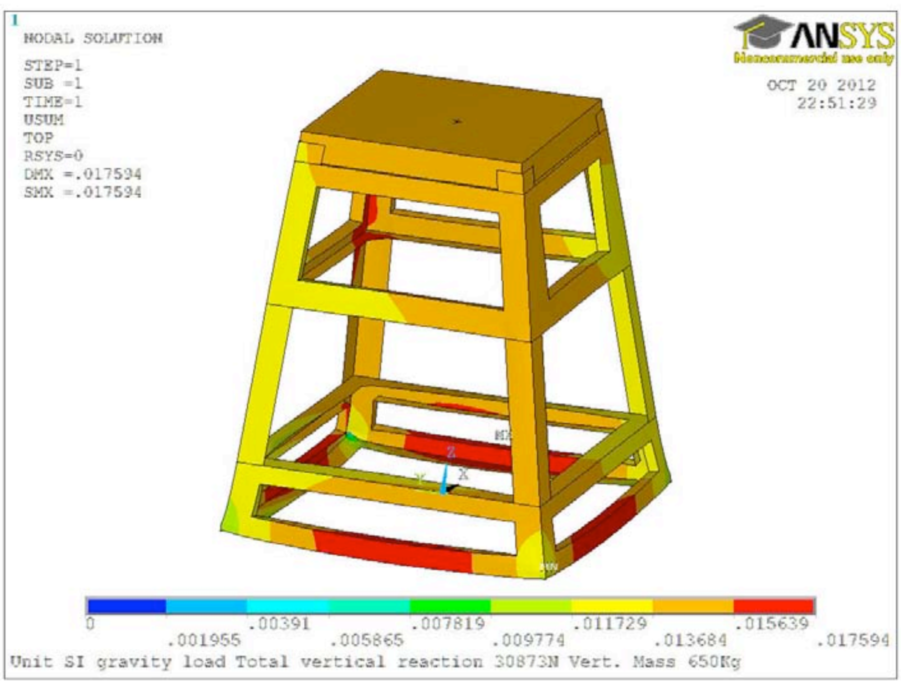
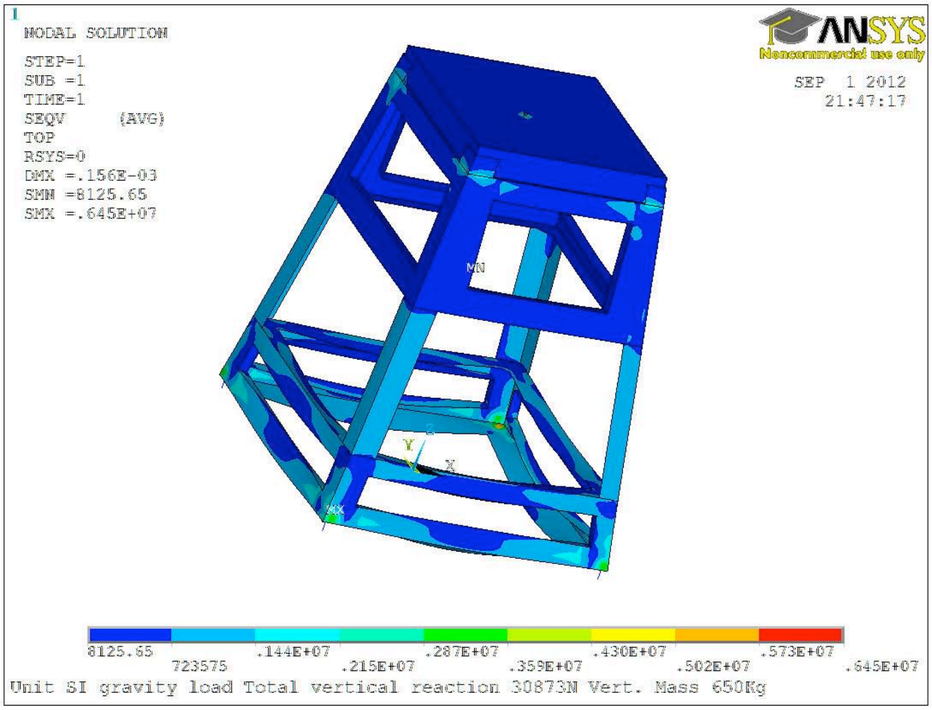


Figure 5

The max equivalent stress with Von Mises criteria are ranging from 3-6.5 Mpa very low for a material considered that have an allowable stress of 160Mpa (See Fig.6)



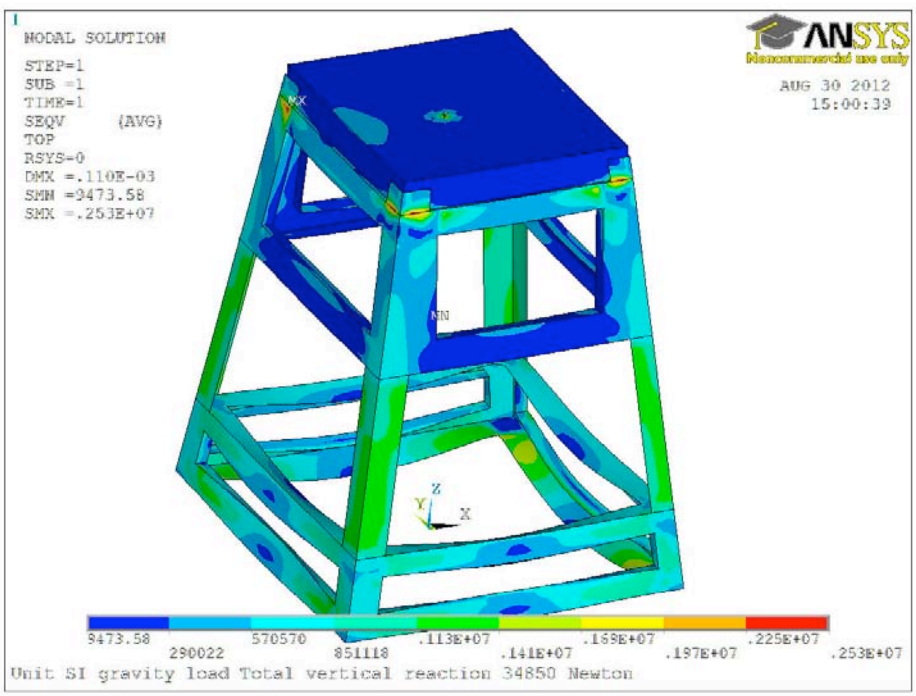


Figure 6

The modal analysis shows, that depending from the constraining method, the first four fundamental modes (two bending and two twist modes) can differ by a factor two. The case in which the base of the frame has all the translational degrees freedom fixed (case three) has frequencies almost equal to case one (see table 1).

This means that when the frame is restrained rigidly to the ground on the four corners the fundamental modes are controlled by the frame stiffness itself.
If the corners restrains are not rigidly connected to the ground, the lower frequencies are affected considerably.
All analyses are performed with the pre-stress due to the gravity weight, however no differences are seen when removing this option, because the stress levels are very low.
The two bending modes have similar frequencies because the structure is almost but not perfectly square (2547 x 2385mm). The same is true also for the third and fourth frequencies, which are related to torsional modes. At higher frequencies internal members start vibrating, they are not affected by the footing choice and have practically no effect to the payload. These higher modes (after the fifth modes) have been moved to higher frequencies by introducing L-profiles braces between the four main L-beams forming the structure. Further increase of the higher modes frequencies is possible adding more local stiffening elements. Damping these modes with rubber dampers is probably the best strategy. We considered that the frequencies of the structure bending and twisting can be affected by internal joints (bolting) that can determine a loss of global stiffness due of insufficient connection between the frame parts. To mitigate this effect a large number of bolts have been foreseen. Furthermore internal dissipation can move the natural frequencies to lower values.

Model with constrained corners Natural frequencies (Hz)	**Model with 100 mm threaded rod raisers Natural frequencies (Hz)**	**Model with fully constrained base Natural frequencies (Hz)**
22.481	13.732	22.722
23.725	13.983	23.963
37.685	21.993	38.139
59.425	48.969	59.474
59.718	50.019	61.548
59.750	53.450	61.725
61.684	57.191	67.579
61.820	58.911	67.790
65.054	59.505	76.491
65.204	60.237	79.887

Table 1

Fig.7 Fundamental mode, bending, for case 1 and 2

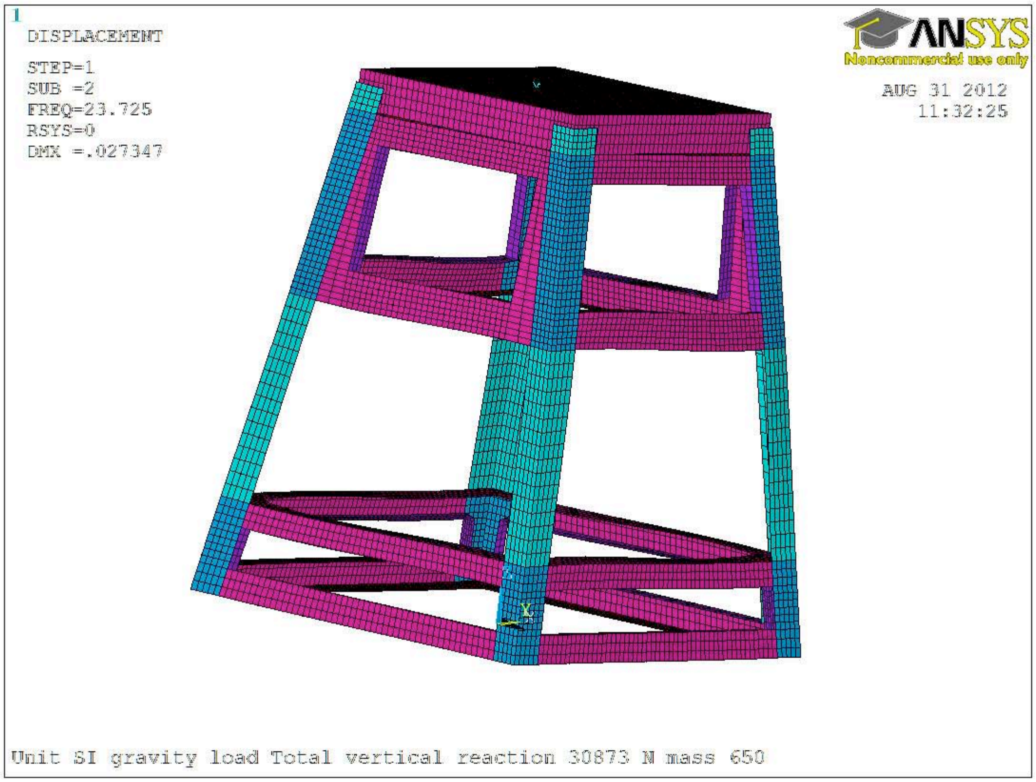


Fig.8 second mode, bending, for case 1 and 2

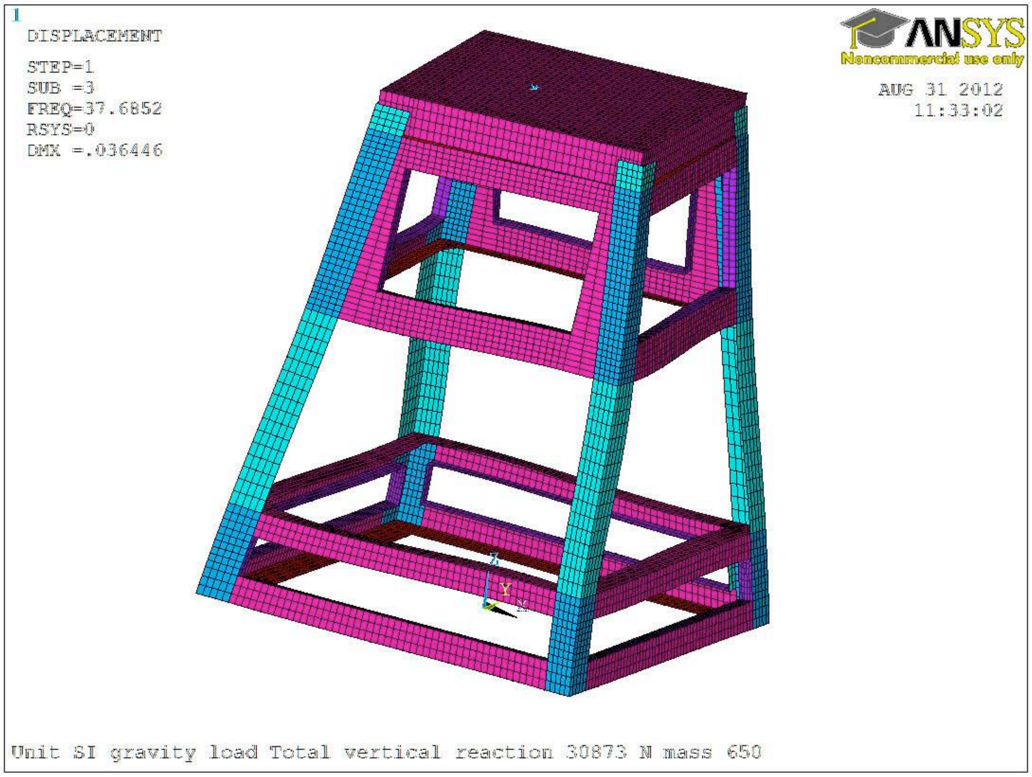


Fig.9 third mode, torsional, for case 1 and 2

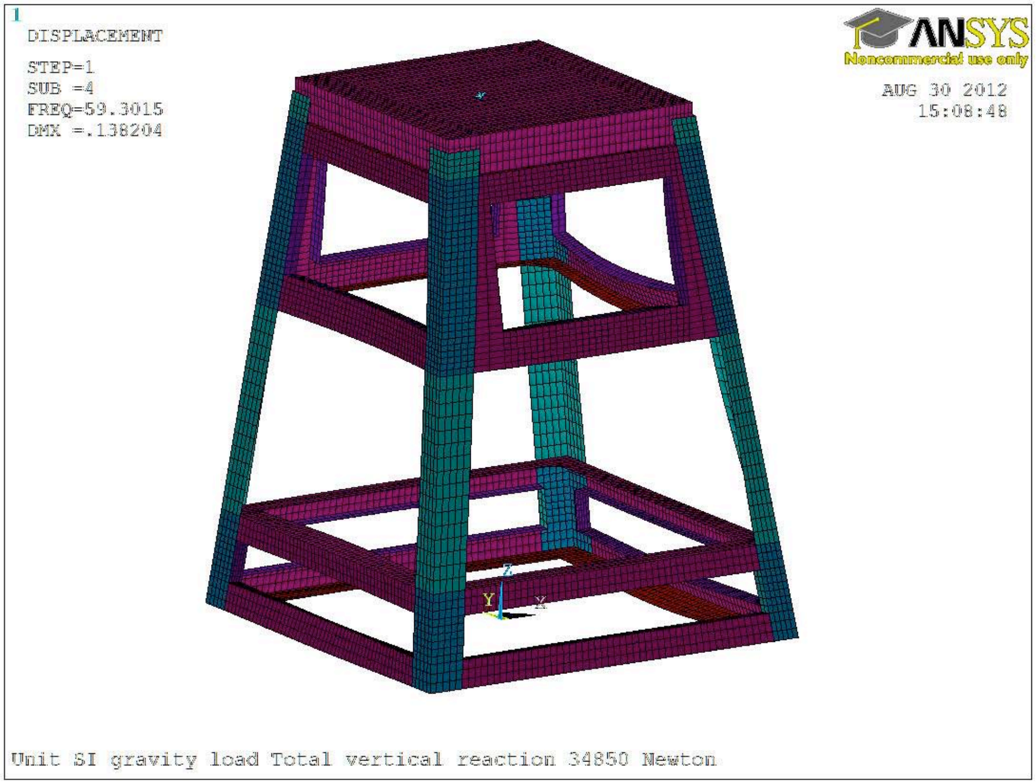


Fig.10 fourth mode, torsional, for case 1 and 2

3.1 Harmonic analysis.

This is performed moving the base of the model horizontally along the y direction by 10^{-3} meter (1mm). We extract the transfer function using the node associated to the lumped mass at the top of the cover plate to evaluate the amplification of the seismic noise due to the resonances as seen by the payload. The frequency range analyzed is between 0-100Hz. Plots are referred to the model with the threaded rod of 100mm.
We consider the ratio from the damping to the critical damping from 4%-7%. Such dissipation value is consistent with a structure that operates in air with a good internal connectivity welded or very well connected with bolts (see table 2-a). Larger dissipation leads to less seismic motion amplification. Calculated amplification levels are resumed in table 2-b.

Damping Factors for Seismic Analysis

	Lower	**High**
Welded steel	2%	4%
Bolted steel	4%	7%
Reinforced concrete	4%	7%
Large diameter piping D>12in	2%	3%
Small diameter pipes D≤12in	1%	2%

Table 2-a, typical damping factors[1].

X-displacement amplification	Y- displacement amplification	Z- displacement amplification	ζ Dissipation value.
0.5	5.5	0.15	0.1
0.19	11.	0.3	0.05
0.14	3.	0.08	0.2

Table 2-b, payload displacement (in mm) for 1 mm excitation in the Y direction for different dissipation factors

[1] The values reported in table 2-a are recommended for doing seismic analysis for nuclear plants (from U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research Washington, DC). For bolted connection the value is between 0.04-0.07, the applied numbers tend to be conservative to be used for estimation of seismic effect with a safety margin so we can expect values even large than 0.07.

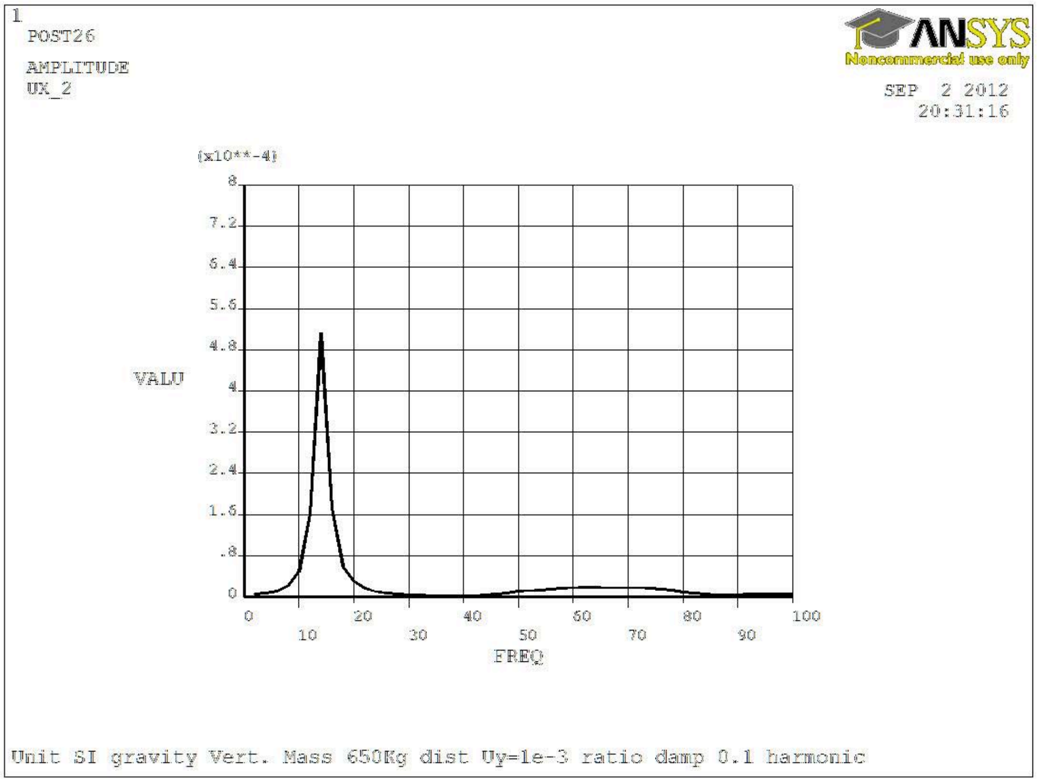


Fig. 11-a lumped mass displacement x, ζ=0.1

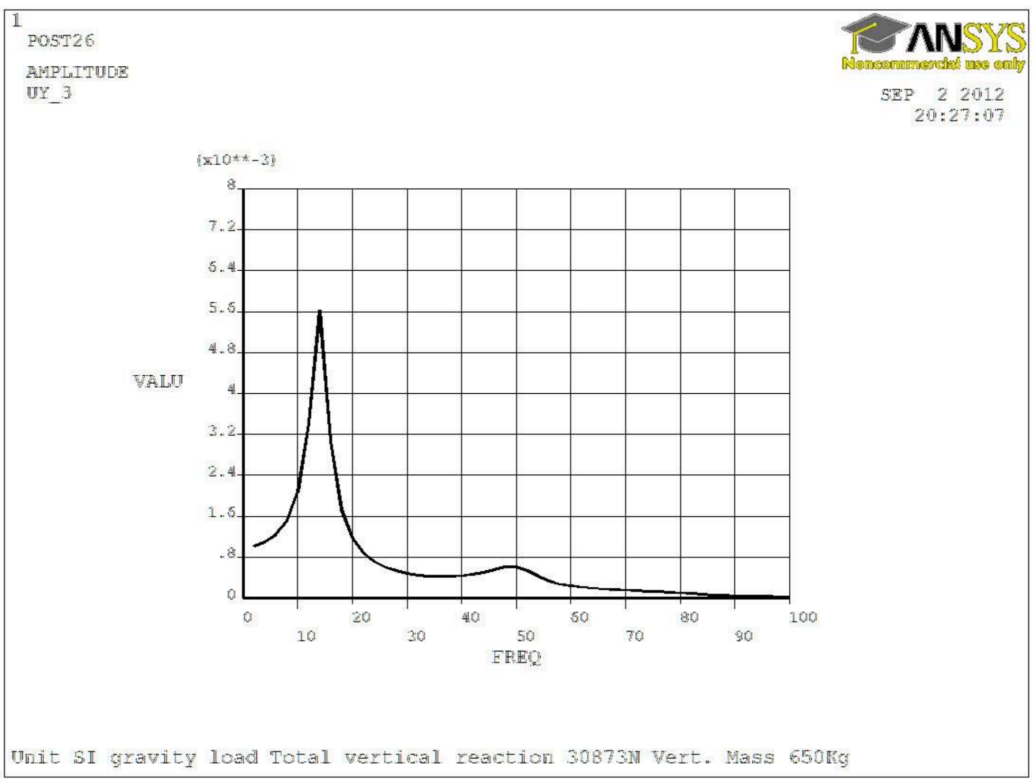


Fig. 11-b lumped mass displacement y, ζ=0.1

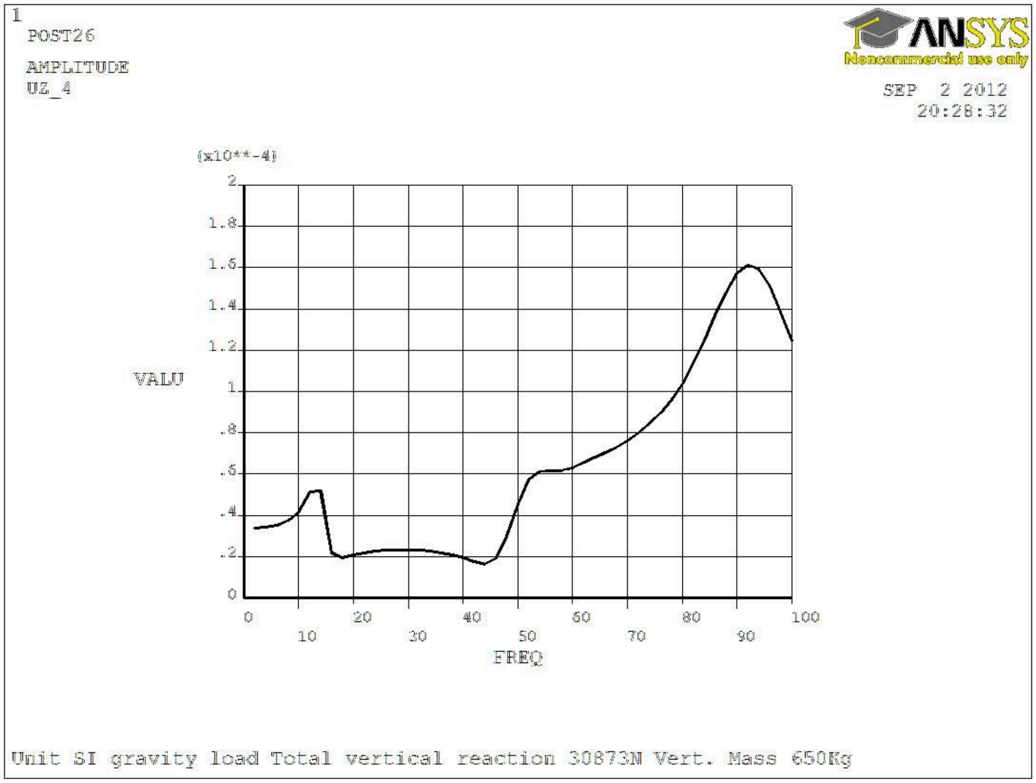


Fig. 11-c lumped mass displacement z, ζ=0.1

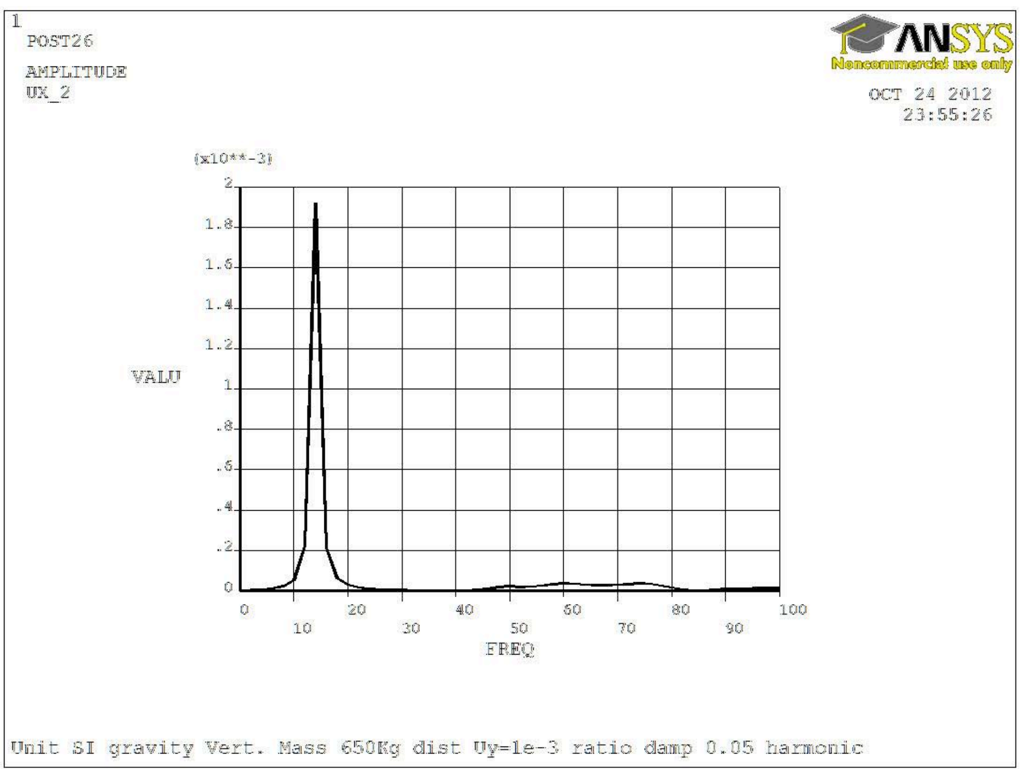


Fig. 12-a lumped mass displacement x, ζ=0.05

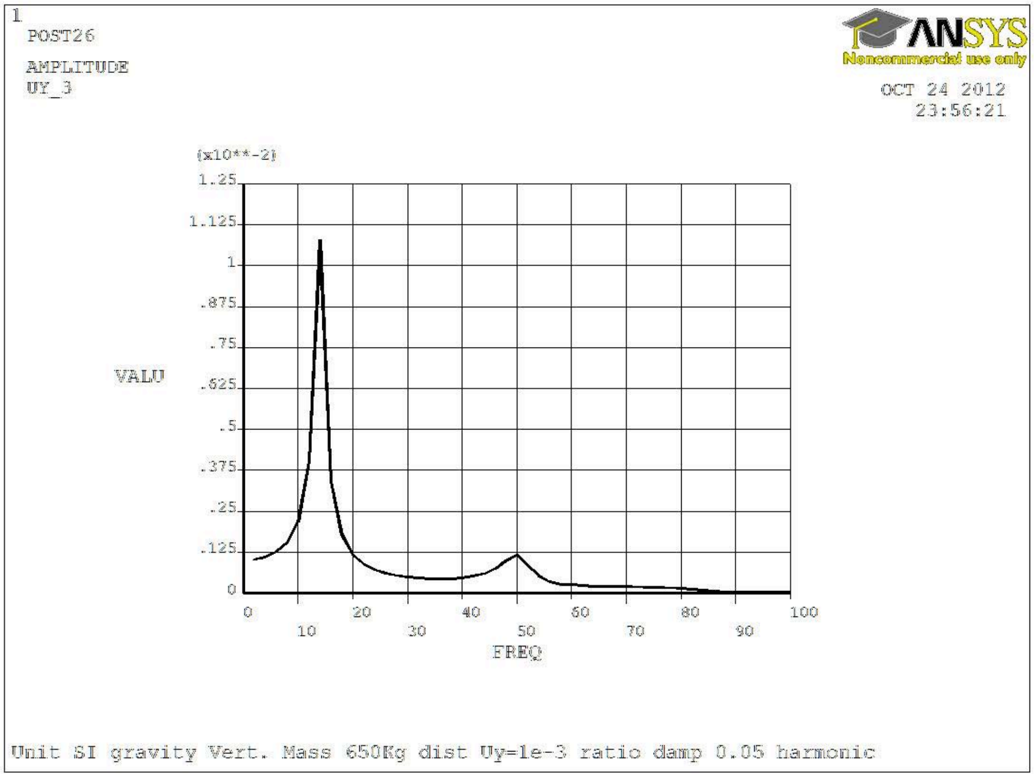


Fig. 12-b lumped mass displacement y, ζ=0.05

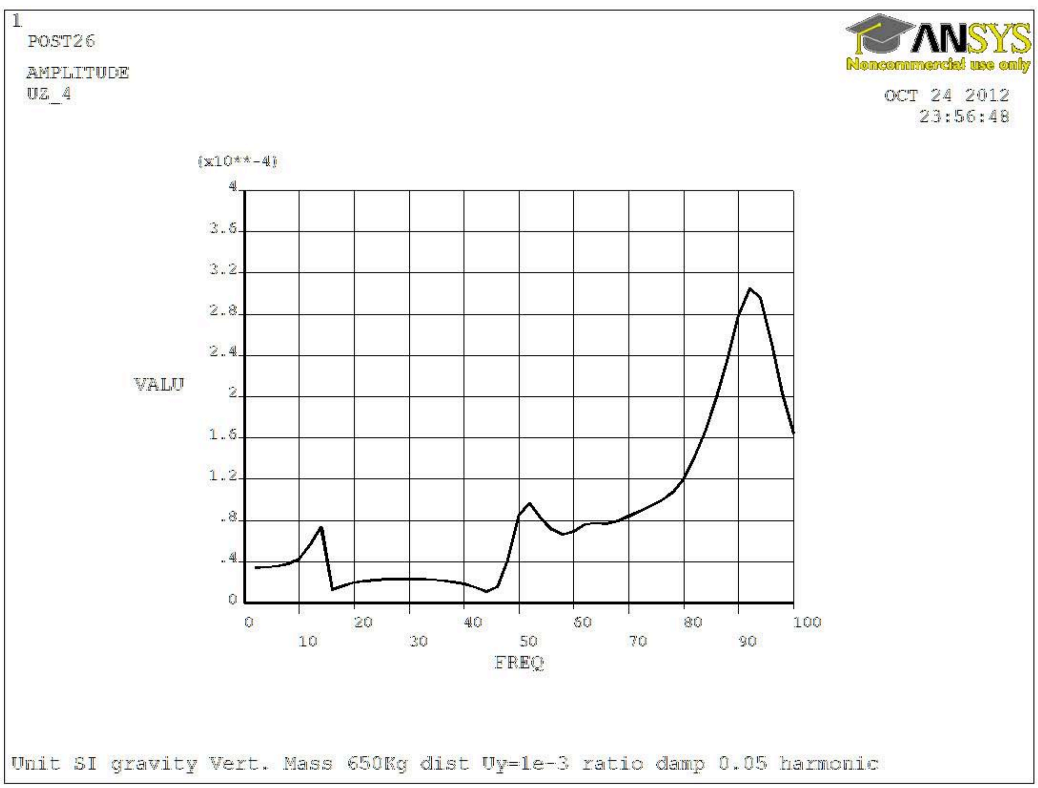


Fig. 12-c lumped mass displacement z, ζ=0.05

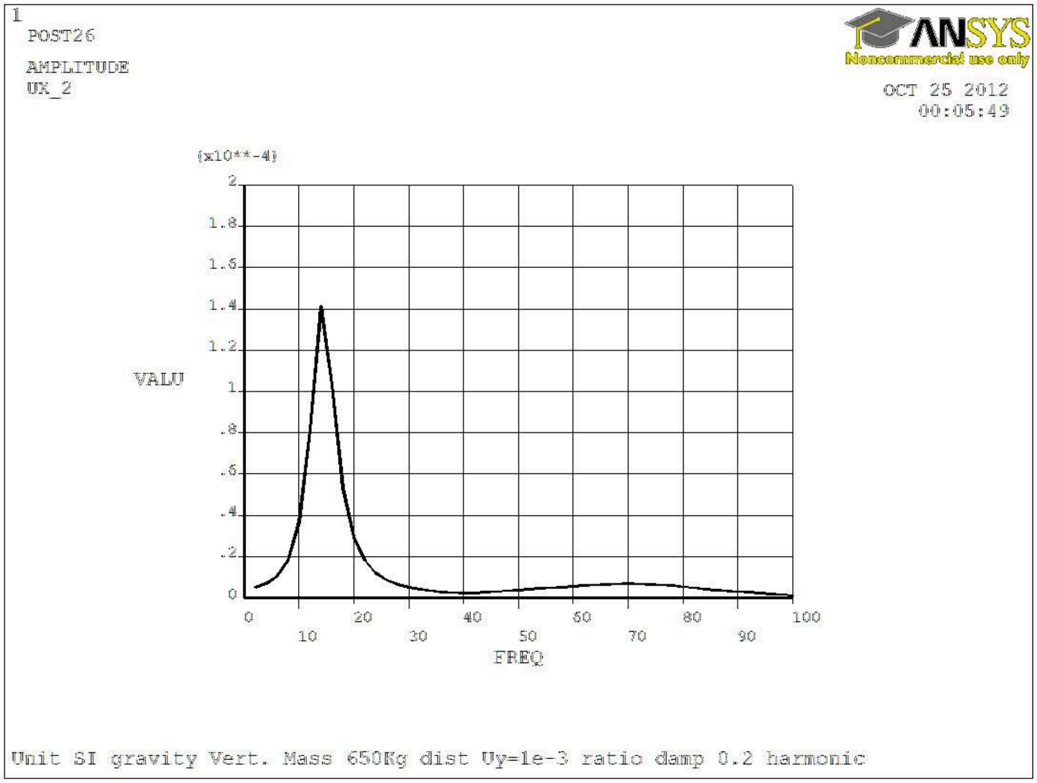


Fig. 13-a lumped mass displacement x, ζ=0.2

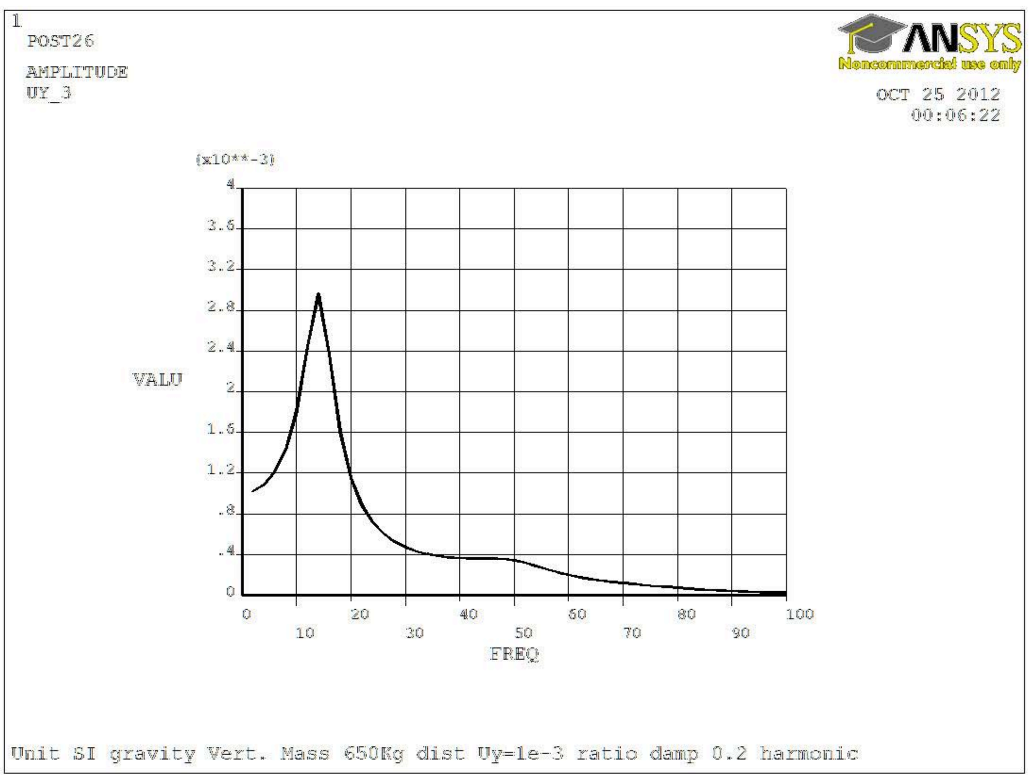


Fig. 13-b lumped mass displacement y, ζ=0.2

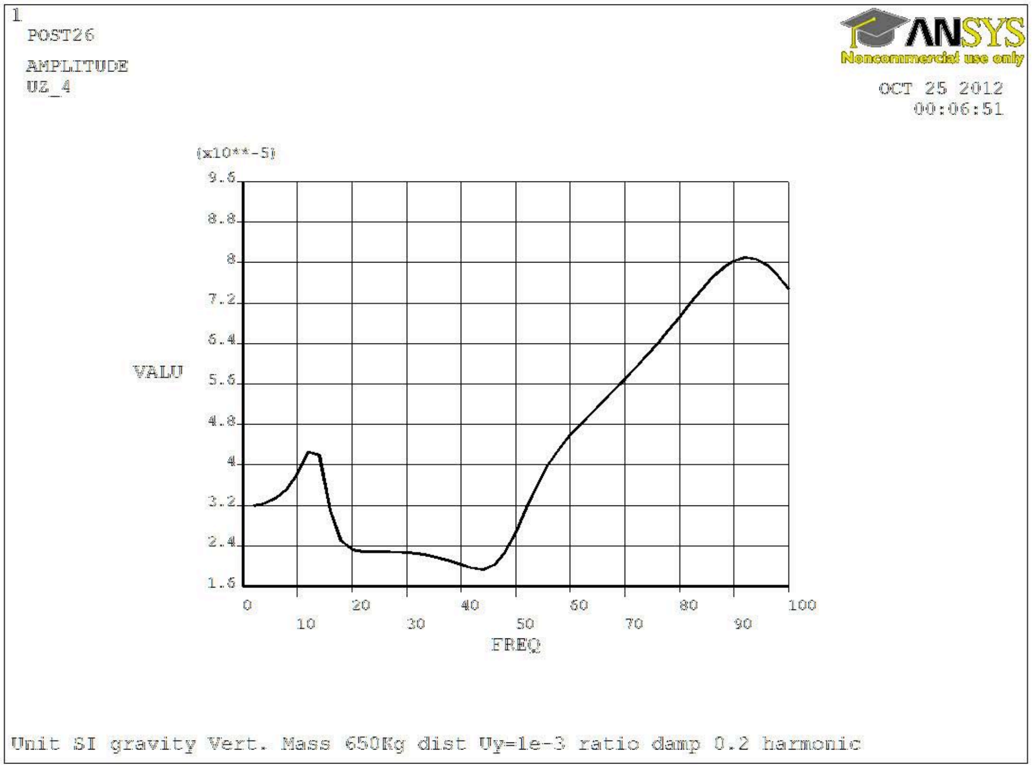


Fig. 13-c lumped mass displacement z, ζ=0.2

4.1 Conclusions.

The modal analysis shows that the fundamental frequencies can be maximized by restraining the four corners of the frame. Increasing the connection to the ground along the entire base does not significantly improve the horizontal modes.
However raisers are needed to adjust the height of the structure. The reduction in stiffness of the connection introduced by the raisers at the four corners of the structure can lower substantially the fundamental frequency, by up to a factor two from 22 to 13 Hz with long raisers. It is important to keep these raisers as short as possible.
The harmonic response analysis is related to the metal dissipation values considered. If we consider reasonable metal dissipation values between 0.05 and 0.1 with the model with threaded rod connections, at the peak frequency 13 Hz the magnification of seismic motion in the direction of the excitation can vary from 5.6 to 10 times the applied displacement at the bottom of the base. Negligible effects are observed in the directions orthogonal to the excitation.
Two strategies are possible to mitigate the effects of the raisers after their height is adjusted to meet the vacuum pipe height requirements.
The free length of the raisers can be constrained and made rigid by means of pairs of horse-shoe wedges. This stiffening will increase the fundamental resonant frequencies.

The free length of the raisers can be encapsulated in a thick layer of heavy damping rubber foam. The rubber in then tightly compressed by an external clamp to expand it vertically between magnetic foot (or the floor) and the structure corner, thus providing effective fundamental mode damping.
A combination of the two solutions can be implemented as well.
Loss of stiffness and dissipation effects at the connection points between parts of the structure can lower the fundamental frequencies but the chosen design of bolt connection is expected to be sufficient to mitigate this effect.
Higher frequencies, above the fourth resonance were moved to higher values, using local stiffening techniques. They do not significantly affect the payload.