Experimental Investigation on Effects of Positioning Pendulum Type Tuned Mass Damper on Different Storey Levels

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Abstract - *A* Pendulum type Tuned Mass Damper (PTMD) is a passive structural vibration control device which consists of a moving secondary mass which is suspended from the main structure and connected to external dampers. Placing PTMD at top or middle or bottom storey levels will have different effects on vibration response of the structure. In the current investigation, effects of positioning PTMD on different storey levels are explored. An actual model of 3 storied framed structures has been fabricated and its response under sinusoidal base excitation is compared with PTMD suspended from different storey levels. Different PTMD frequency, mass and positions were considered and model is tested for base excitations using shake table analysis. The PTMD without damping is used and only the effect of variation in frequency ratio, mass ratio and position is considered. The response of the structure was experimentally determined and compared for different PTMD locations. The results show significant reduction in acceleration and maximum displacement of the actual model when the PTMD is placed at the top floor. Best result occurs when the PTMD is on the top floor and the frequency ratio is 1. When PTMD is tuned for the 1st modal frequency, placing it on 2nd or 1st floor makes it very ineffective and in some case increases the acceleration and displacement response of the structure.

Key Words: Pendulum type Tuned Mass Damper, PTMD position, Resonance, Seismic resistance, Shake table analysis

1. INTRODUCTION

Natural hazards like earthquake and wind presents an important problem of structural vibrations in tall and huge structures. Depending on their intensity, exterior vibrations can cause problems ranging from minor discomfort for the occupants to severe structural harm or even collapse [1]. Latest design methods use the inelastic deformations to dissipate the energy and mitigate the vibration problem. Many older structures might not have been designed for resisting earthquake loads. Hence external energy dissipation devices are used to augment the performance of newer and older structures. One of such device is a Tuned Mass Damper (TMD). TMD is a passive vibrational control device which consists of an additional mass placed inside the main structure which is connected to the main structure via springs and dampers this allows it to move with respect to the main structure. When the structure is excited by the external forces, it also imparts motion to the TMD, which produces restoring forces which are out of phase with the external vibrating forces due to which the structural vibration response is reduced [2]. The TMD is used to avoid resonance in the main structure. Resonance occurs when the frequency of external force is same as the natural frequency of the structure [3]. Thus if the frequency of the TMD is kept near to the natural frequency of the primary structure, a significant reduction in response of the structure for that forcing frequency can be achieved [4].

The idea of TMD was originated by Frahm [5] who used a spring absorber then Den Hartog [6] first provided the optimization method for undamped system. Since then many different types of TMD have been designed. One of which is a Pendulum type Tuned Mass Damper (PTMD). PTMD works very similar to a TMD the only difference is that in TMD the secondary mass has translating motion but in PTMD the secondary mass is suspended from the main structure hence it swings like a pendulum. Dampers are also provided to the PTMD to dissipate the kinetic energy and it also helps in reducing the distance by which the PTMD moves. Conventionally, the PTMD is provided at the top storeys of the structure like the PTMD from the 92nd floor in the Taipei 101 building [7]. The main reason of this is that the TMD should be placed at the location where the maximum amplitude of the particular mode shape occurs [2]. But if due to some circumstances the PTMD is provided on the middle or bottom story levels, and if it is not tuned properly, the PTMD will work inadequately or even worsen the vibration response of the structure [8].

The tuning of TMD is done by finding optimal parameters which are Mass ratio (μ), Frequency ratio (f_r) and Damping ratio (ζ), these parameters are defined as follows,

$$\mu = \frac{\text{Mass of TMD}}{\text{Mass of structure}} \tag{1}$$

$$f_r = \frac{\text{Frequency of TMD}}{\text{Frequecy of structure}} \tag{2}$$

$$\zeta = \frac{\text{Actual damping coefficient of TMD}}{\text{Critical damping coefficient of TMD}} \tag{3}$$

A Multi Degree of Freedom (MDOF) structure has multiple natural frequencies for different mode shapes [3]. The TMD is tuned to a particular modal frequency and this modal frequency is the dominant mode of the structure whose amplitude is highest compared to other modes. A TMD without damper can be tuned to reduce the response of the structure for a single natural frequency of the dominant mode. But when TMD is added to the structure, it adds an extra degree of freedom in the structure and due to this there is an additional modal frequency at which resonance of the structure can occurs [9, 10] hence to reduce the response of TMD and structure at this new frequency, the optimal damping is necessary otherwise at this frequency the TMD will be less effective to reduce the response.

Although a damper is an important element in TMD, in the current work, a PTMD is used without the damper. The main objective is to observe how the structural response changes when the PTMD which is tuned to reduce the structural response at the 1st dominant mode is provided on different storey levels. For this an actual model of 3 storied frame structure with PTMD is tested for the base excitations having frequency same as dominant mode of the structure and different mass ratios and frequency ratios of the PTMD are also considered.

Till now multiple studies are carried out to determine optimal parameters for PTMD and derive equation for the same. Abubakar and Farid (2009) [11] obtained a generalized equation for tuned mass damper was made considering the damping in the main structure, which was not included in Den Hartog's work. Yanhui Liu, et al. (2020) [12] carried out numerical and experimental analysis to find optimal parameters for TMD for MDOF structure. Gino B. Colherinhas, et al. (2019) [13], found out optimal parameters for a MDOF structure by considering equivalent SDOF system. Rafik R. Gerges and Barry J. Vickery (2005) [14], provided equations for optimal parameters for different systems with and without damping having different forcing conditions. They also found out PTMD to be more effective for wind excitation than earthquake excitations. Pedro L. Bernardes Júnior, Marcus V. G. de Morais, Suzana M. Avila (2019) [15],Experimentally analysed an inverted PTMD and experimentally found out optimal parameters for MDOF structure and was able to reduce structural response for a range of frequencies.

2. MATERIALS AND METHODS

In the current study, a 3 storied frame structure without infill wall was considered which was provided with PTMD suspended from 1st, 2nd and 3rd floor (one floor at a time). An actual model of the structure was fabricated which consists of 3 rigid floor slabs supported by 4 columns. The columns are rigidly fixed to the base. Fig. 1 (a) and Fig. 1 (b) are diagram showing the model elevation and plan respectively. Table 1 shows the material properties. The model is tested with PTMD suspended from different floors for sinusoidal (harmonic) base excitation using shake table testing. The vibration response of the structure with and without PTMD is measured and compared.

The model is symmetric and the center of mass coincides with the center of stiffness. The PTMD is suspended from the center of mass on each floor.

Table -1: Model properties [16]

Structural Member	Dimension and Material Property
Slab Properties	Material = Plywood, Dimensions: Length= 360 mm, Width = 260mm, Thickness = 12mm, Density = 8.458 KN/m^3, Longitudinal Modulus of Elasticity = 10800 MPa, Longitudinal Poisson's ratio = 0.3, Longitudinal Modulus of Rigidity = 4154 MPa.

Column Properties	Material = Aluminium, Dimensions: Width = 19 mm, Thickness = 2 mm, Density = 27.1 KN/m^3, Modulus of Elasticity = 70000 MPa, Poisson's ratio = 0.32, Modulus of Rigidity= 26516 MPa.

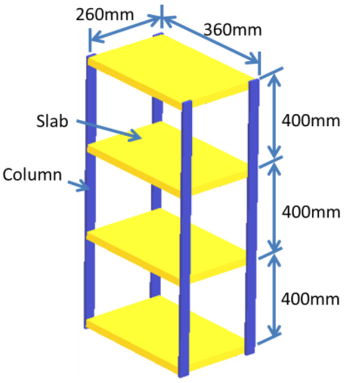


Fig -1: Frame Structure 3d View

3. FREE VIBRATION TEST

The actual model shown in Fig. 4 was fabricated which had mass of 3500gm. To find out modal frequencies of actual model, free vibration test was conducted. For free vibration test, the base of the model was kept fixed and the top floor was given an initial displacement along the longer span of the model. Acceleration of top floor was measured during the free vibration and Fast Fourier Transform (FFT) was carried out on the acceleration vs time data to find out the natural frequencies. Fig 2 and Fig 3 shows recorded free vibration data and its FFT respectively.

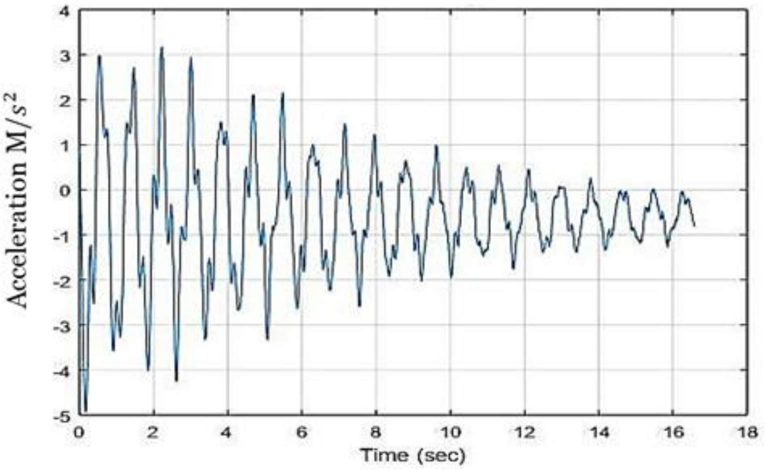


Fig -2: Free Vibration Acceleration vs Time Graph

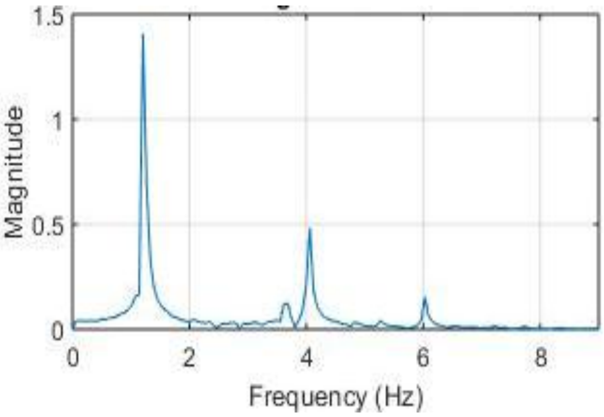
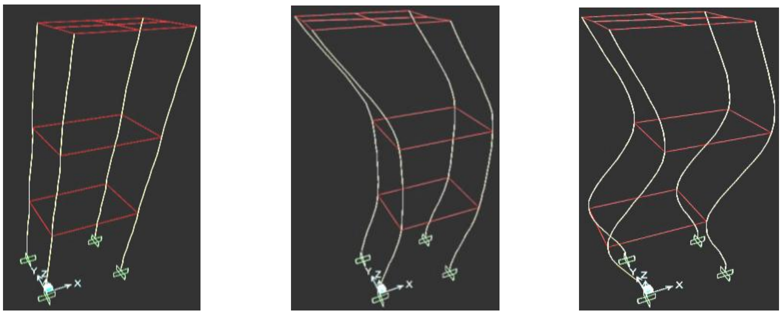


Fig -3: Fourier Transform of Acceleration Vs Time Data

Fig -4: Actual Model

The peaks of FFT graph shows the natural frequencies of the structure which were 1.2 Hz, 4 Hz and 6 Hz, these correspond to the 1st, 2nd and 3rd translational mode respectively. The diagrams of1st, 2nd and 3rd translational mode shapes are shown in Figure 5 (a), Figure 5 (b) and Figure 5(c) respectively.



(a) (b) (c)

Fig -5: Mode Shapes

4. SHAKE TABLE TEST (WITHOUT PTMD)

To test the structure under resonant condition, the actual model was tested for sinusoidal base excitations having frequencies 1.2Hz (1st modal frequency) and 4Hz (2nd modal frequency). For this, shake table testing was used. The amplitude of shake table excitation was kept as 5mm. For these tests maximum amplitude of displacement occurred at top floor. Hence acceleration of top floor and also the shake table were measured. From top floor acceleration and shake table acceleration, relative displacement between top floor and base was calculated. Figure 6 shows the graphs of relative displacement for 1.2Hz base excitation and Figure 7 shows relative displacement for 4Hz base excitation. The observed maximum of top floor relative displacement for 1.2Hz base excitation was 78.86 mm and for 4Hz base excitation it was 18.88 mm.

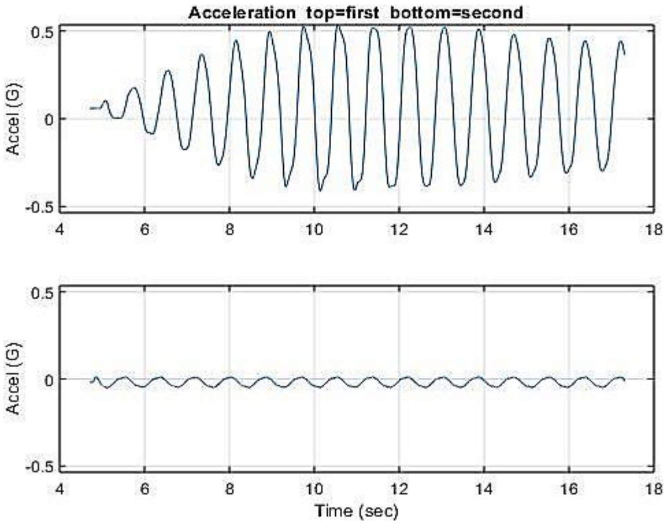


Fig -6: Top (3rd) floor and bottom floor (base) accelerations (1.2 Hz base excitation)

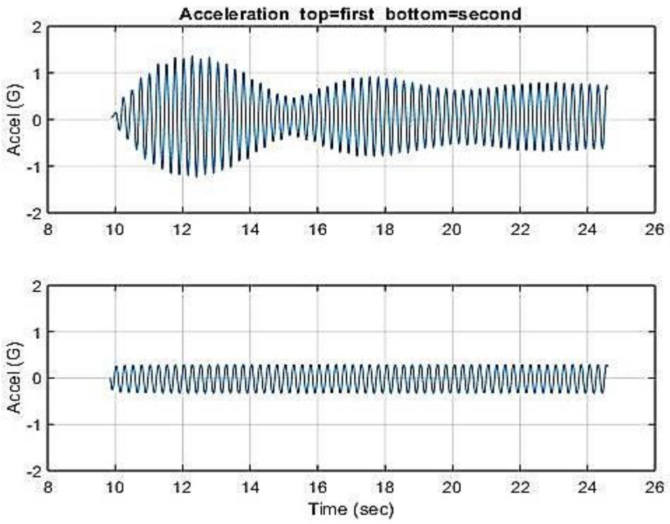


Fig -8: Top (3rd) floor and bottom floor (base) accelerations (4 Hz base excitation)

5. SHAKE TABLE TEST (WITH PTMD)

The PTMD setup consisted of a weight suspended from bottom of the floor using a relatively massless rod. The PTMD was suspended from 3rd, 2nd, and 1st floor one floor at a time as shown in Figure 8(a), Figure 8(b) and Figure 8(c) respectively, and different mass ratio = 0.05, 0.1, 0.15 and different frequency ratio = 0.8, 1, 1.3 were considered and tested for sinusoidal base excitation for two different frequencies 1.2 Hz and 4 Hz keeping the amplitude 5mm. The acceleration of top floor and shake table were measured for the tests with 1.2 Hz base excitation. For the tests where the base excitation frequency was 4 Hz and PTMD was at top floor, the maximum displacement was occurring on the 2nd floor hence the acceleration of 2nd floor and shake table were measured for those tests. Relative displacement data was calculated from acceleration readings.

Although for high rise buildings, mass ratio is limited to 5% [17], larger mass ratios were considered for the test to determine effect of change in mass ratio.

(a) (b) (c)

Fig -8: PTMD Attached on 3rd, 2nd and 1st Floor

The graphs of relative displacement of top floor with respect to the base of several tests are as follows.

(The application of base excitations begins at 10 second mark and the vibrations after the 10 second mark are considered for the structural response).

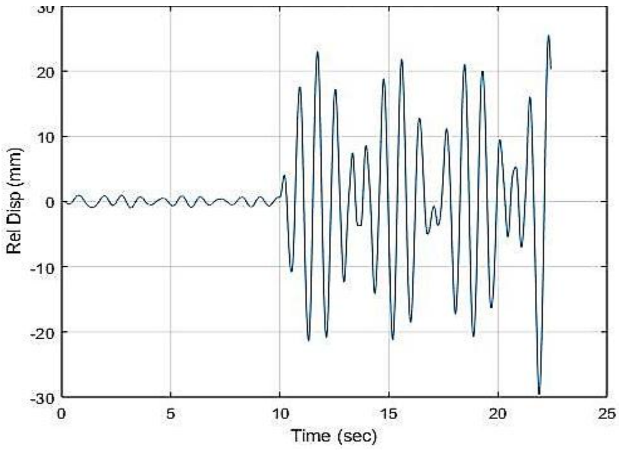


Fig -9: Relative displacement (PTMD on 3rd floor) (1.2Hz base frequency) (μ=0.05, f_r=1)

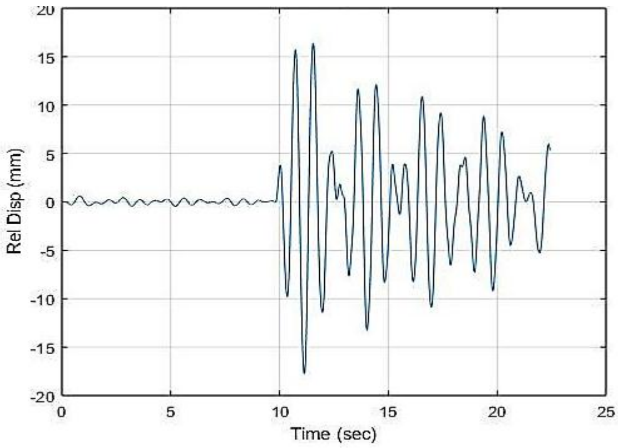


Fig -10: Relative displacement (PTMD on 2nd floor) (1.2Hz base frequency) (μ=0.05, f_r=1)

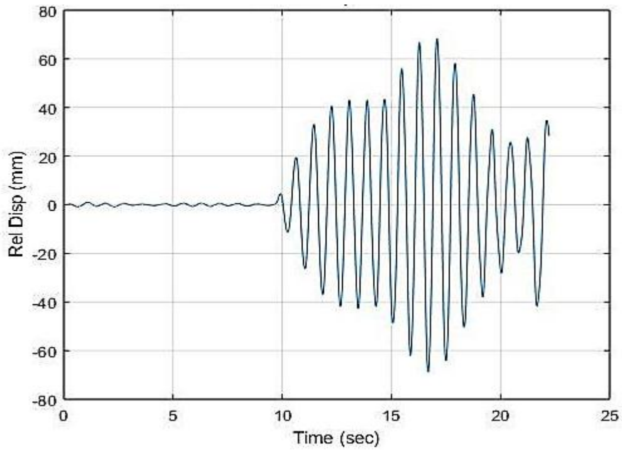


Fig -11: Relative displacement (PTMD on 1st floor) (1.2Hz base frequency) (μ=0.05, f_r=1)

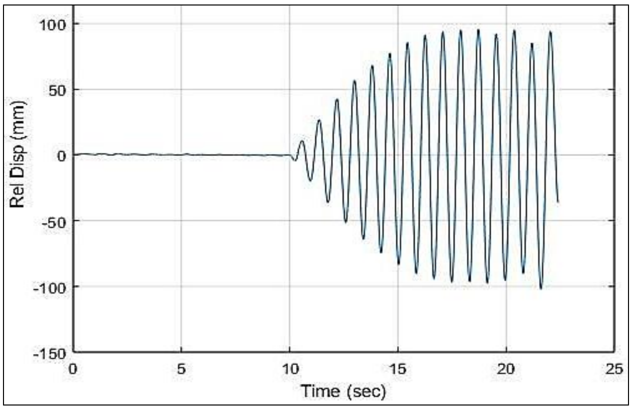


Fig -12: Relative displacement (PTMD on 1st floor) (1.2Hz base frequency) (μ=0.05, f_r=1.3)

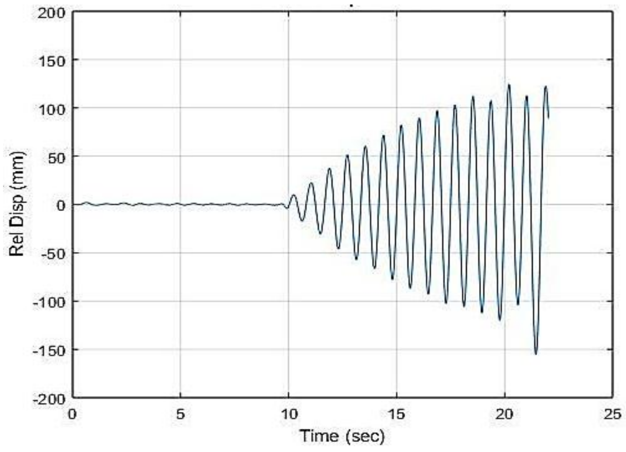


Fig -13: Relative displacement (PTMD on 2nd floor) (1.2Hz base frequency) (μ=0.05, f_r=1.3)

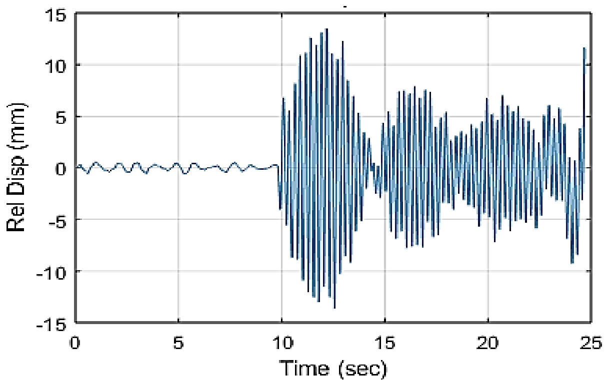


Fig -14: Relative displacement of 2nd floor w.r.t. base (PTMD on 3rd floor) (4Hz base frequency) (μ=0.05, f_r=1)

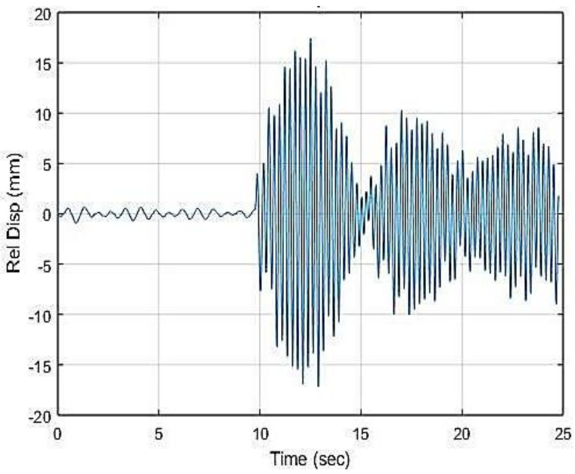


Fig -15: Relative displacement (PTMD on 2nd floor) (4Hz base frequency) (μ=0.05, f_r=1)

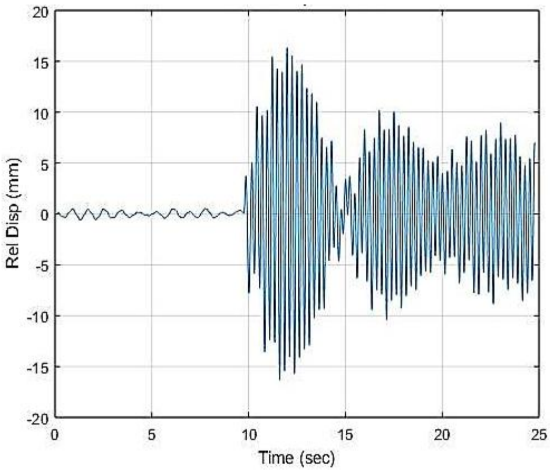


Fig-16: Relative displacement (PTMD on 1st floor) (4Hz base frequency) (μ=0.05, f_r=1)

6. RESULTS AND DISCUSSION

Following are the maximum relative displacements. (Maximum displacement without PTMD for 1.2Hz excitation was 78.86mm and for 4Hz it was 18.88mm)

Table -2: Maximum Displacement of Top Floor (mm) (PTMD Position 3rd Floor) (1.2 Hz base excitation)

f_r \ μ	0.05	0.1	0.15
0.8	42.94	27.81	20.1
1	16.97	13.08	11.93
1.3	67.15	31.93	24.41

Table -3: Maximum Displacement of Top Floor (mm) (PTMD Position 2nd Floor) (1.2 Hz base excitation)

f_r \ μ	0.05	0.1	0.15
0.8	49.32	41.54	31.13
1	29.65	16.82	14.38
1.3	124	50.38	37.78

Table -4: Maximum Displacement of Top Floor (mm) (PTMD Position 1st Floor) (1.2 Hz base excitation)

f_r \ μ	0.05	0.1	0.15
0.8	67.12	64.92	61.05
1	68.88	43.34	27.02
1.3	102.2	131.1	144.4

Table -5: Maximum Displacement of 2nd Floor (mm) (PTMD Position 3rd Floor) (4 Hz base excitation)

μ f_r	0.05	0.1	0.15
0.8	14.36	13.99	12.86
1	13.83	13.38	12.71
1.3	14.01	13.73	12.48

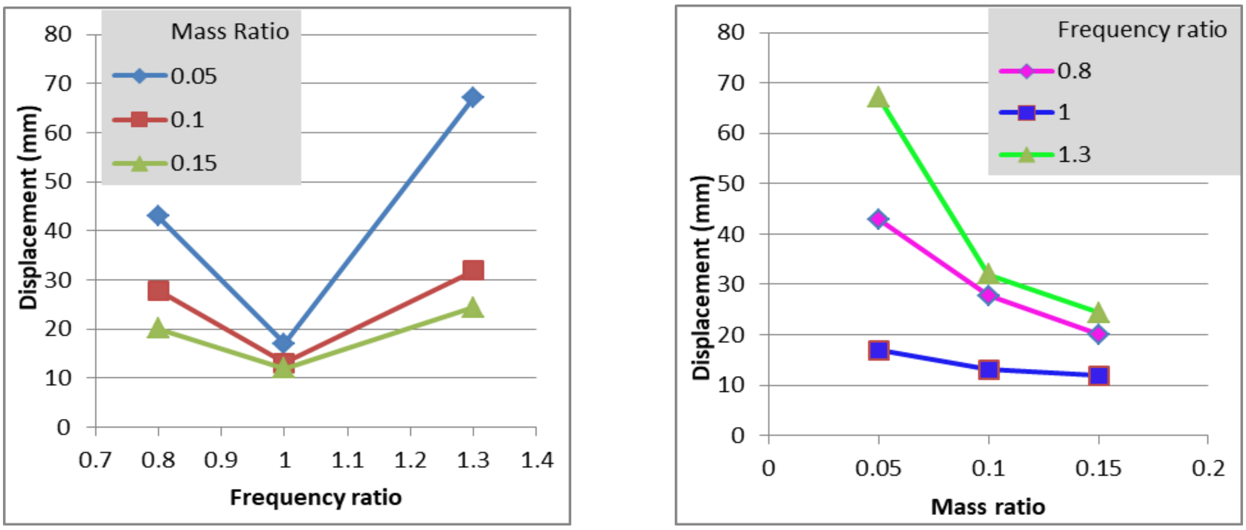
Table -6: Maximum Displacement of Top Floor (mm) (PTMD Position 2nd Floor) (4 Hz base excitation)

μ f_r	0.05	0.1	0.15
0.8	18.23	16.39	15.14
1	17.46	16.93	19.93
1.3	18.34	21.41	15.93

Table -7: Maximum Displacement of Top Floor (mm) (PTMD Position 1st Floor) (4 Hz base excitation)

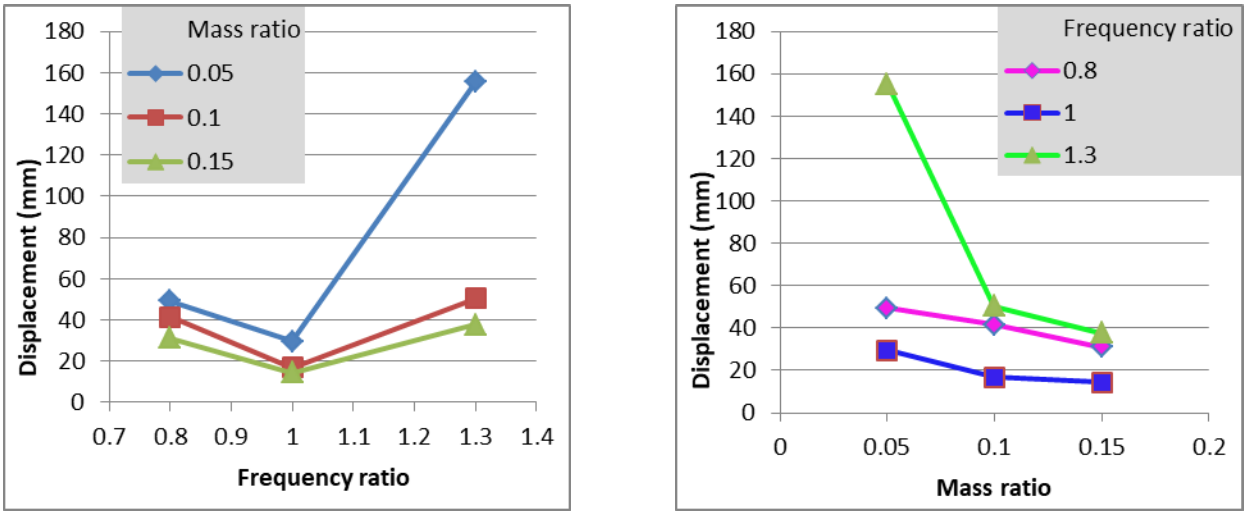
μ f_r	0.05	0.1	0.15
0.8	22.01	17.09	16.04
1	16.33	16.03	16.11
1.3	18.5	17.25	16.19

Following are the graphs of displacement vs frequency ratio and displacement vs mass ratio.



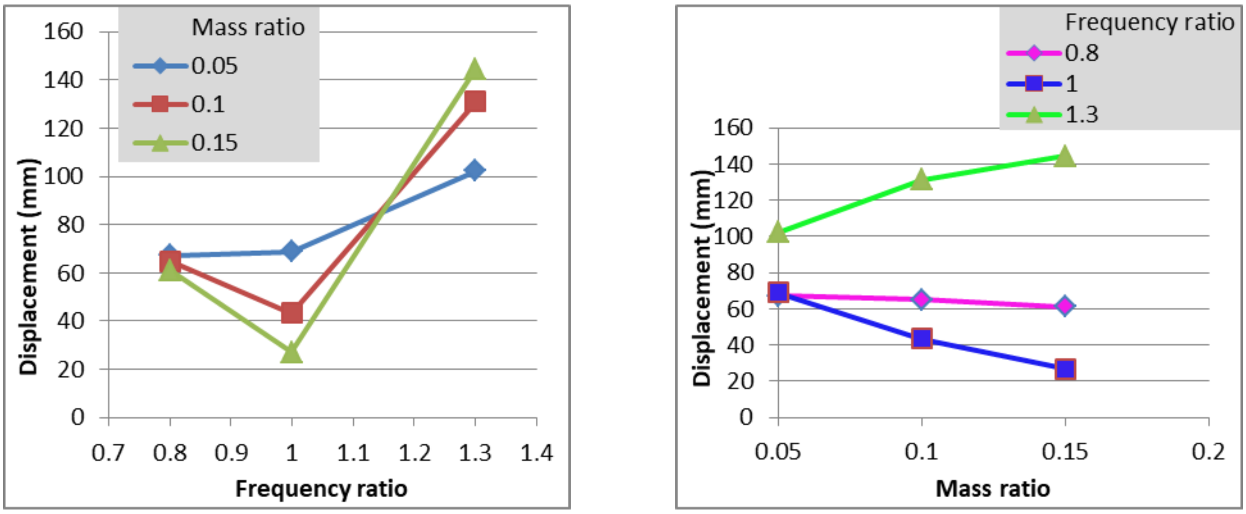
(a) (b)

Chart -1: Maximum Displacement of Top Floor (mm) (PTMD on 3rd Floor) (1.2 Hz base excitation)



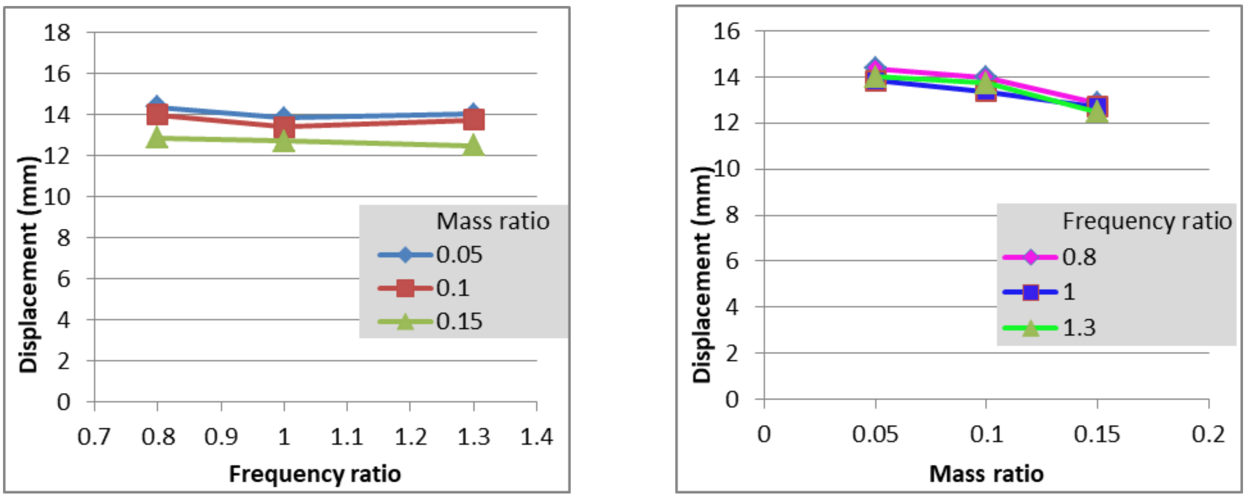
(a) (b)

Chart -2: Maximum Displacement of Top Floor (mm) (PTMD on 2nd Floor) (1.2 Hz base excitation)



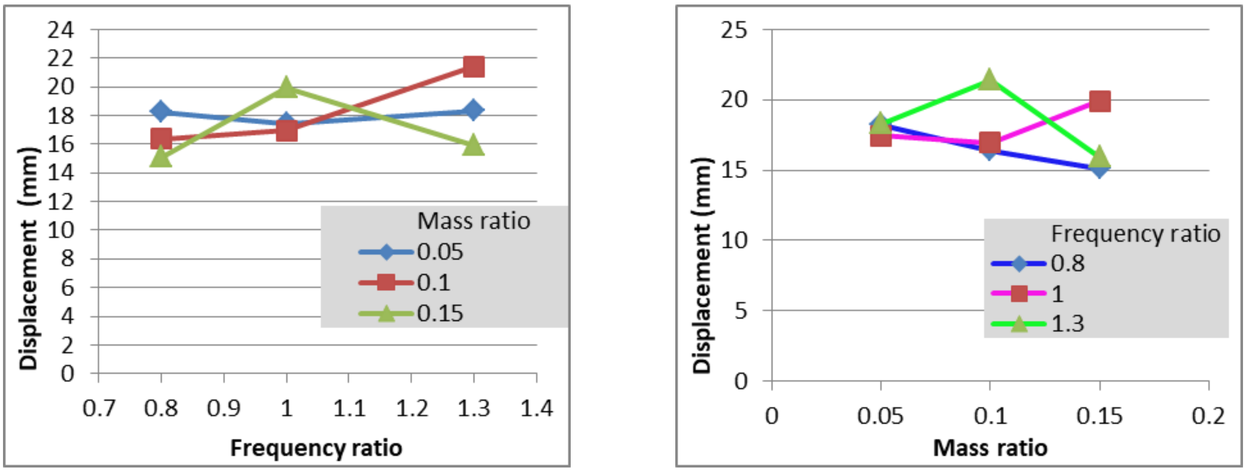
(a) (b)

Chart -3: Maximum Displacement of Top Floor (mm) (PTMD on 1st Floor) (1.2 Hz base excitation)



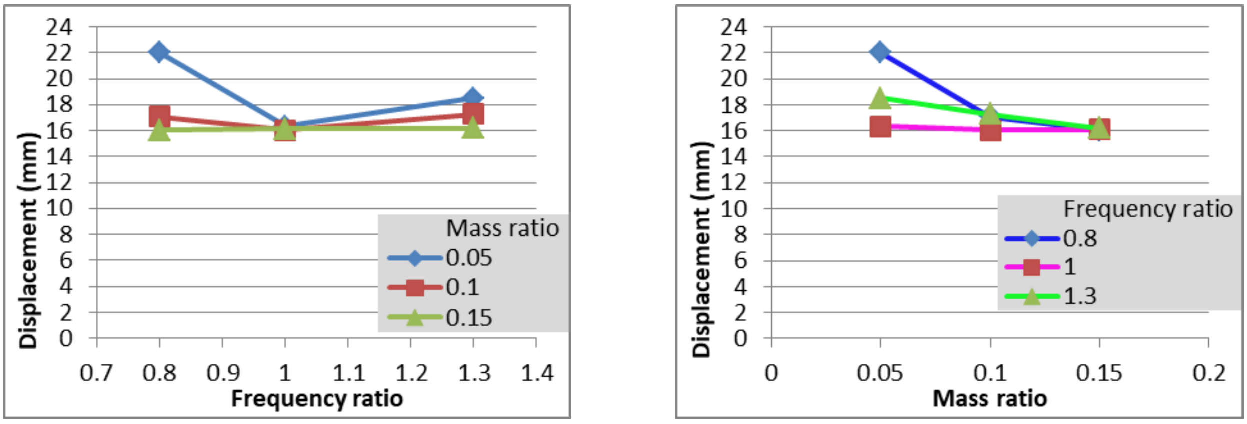
(a) (b)

Chart -4: Maximum Displacement of 2nd Floor (mm) (PTMD on 3rd Floor) (4 Hz base excitation)



(a) (b)

Chart -5: Maximum Displacement of Top Floor (mm) (PTMD on 2nd Floor) (4 Hz base excitation)



(a) (b)

Chart -6: Maximum Displacement of Top Floor (mm) (PTMD on 1st Floor) (4 Hz base excitation)

6.1 Discussion of the results

Following are the graphs of acceleration response of the structure with and without PTMD for 1.2Hz and 4Hz base excitation (PTMD located on 3rd floor).

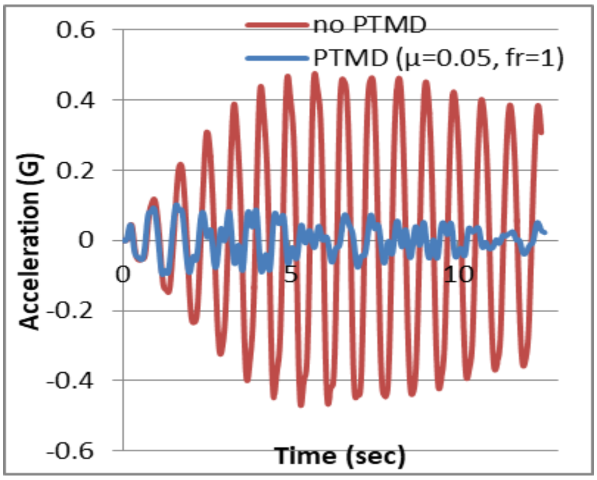


Chart -7: Acceleration response of 3rd floor with and without PTMD (1.2Hz excitation)

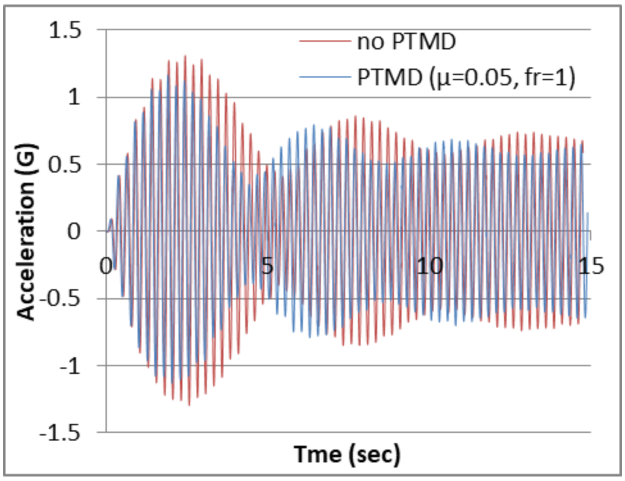


Chart -8: Acceleration response of 2nd floor with and without PTMD (4Hz excitation)

PTMD location 3rd floor

At 1.2Hz excitation frequency resonance was observed, hence the PTMD was tuned for this frequency. From the results it is observed that when the PTMD frequency ratio of 1 is suspended from the 3rd floor, significant reduction in the response of the structure occurs for the 1.2Hz base excitations as shown in chart 7. This is because for the mode shape at 1.2Hz base excitation, the maximum amplitude of vibration occurs on the 3rd floor and as stated earlier, the PTMD should be suspended from the point of maximum amplitude for optimal results. Also due to PTMD, resonance was prevented and a steady state response of the structure was achieved. The PTMD suspended from the 3rd floor having $\mu=0.05$, $f_r=1$ gives 78.4% reduction in maximum displacement. The reduction in maximum displacement is calculated from following equation.

$$\%\ \text{Reduction in displacement} = \frac{\text{Maximum disp. without PTMD} - \text{Maximum disp. with PTMD}}{\text{Maximum disp. without PTMD}} \times 100$$

From Chart 1 (a) it is observed that $f_r=1$ gives the best results. When increasing or decreasing the frequency ratio from 1, it makes PTMD less effective in reducing the displacement for 1.2Hz excitation.

From displacement vs mass ratio data it is observed that Increasing mass ratio from 0.05 to 0.1 gives some improvement in reducing the maximum displacement. But increasing mass ratio from 0.1 to 0.15, gives only a slight improvement in reducing the maximum displacement.

For the tests with base excitation frequency of 4Hz, changing the frequency ratio from 0.8 to 1 and from 1 to 1.3 does not provide any significant difference in reducing the maximum displacement. And when the mass ratio is changed from 0.5 to 0.15, only a slight improvement is observed in reducing the maximum displacement. The PTMD with $\mu=0.05$, $f_r=1$ gives 26.7% reduction in maximum displacement.

PTMD location 2nd floor

PTMD suspended from 2nd floor is less effective at displacement reduction than PTMD positioned on 3rd floor for 1.2Hz base excitation. For 1.2 Hz excitation and PTMD on 2nd floor, frequency ratio of 1 is better than frequency ratio of 0.8 and 1.3. And reducing the frequency ratio from 1 makes PTMD less effective. Also worst case occurs when PTMD has $\mu=0.05$, $f_r=1.3$, For this case The maximum displacement observed is 124 mm which is greater than the maximum displacement of the structure without the PTMD. For this case, resonance of the structure is observed for 1.2Hz excitation, which is far worse than the structure without PTMD. For this case, increasing the mass ratio to 0.1 gives some improvement.

Steady state response is observed for 1.2Hz excitation when PTMDs has frequency ratio of 0.8 and 1. For these cases, when increasing mass ratio from 0.05 to 0.1, a slight improvement is observed in reducing the maximum displacement. Also increasing mass ratio from 0.1 to 0.15 provided negligible improvement.

Considering the PTMD with $\mu=0.15$, $f_r=1$, for 4 Hz base excitation, the maximum displacement was more than the maximum displacement of the structure without PTMD. Changing the PTMD parameters did not provide any significant improvement.

PTMD location 1st floor

The PTMD suspended from 1st floor was observed to have the worst performance. When the frequency ratio is 1.3, resonance of the structure is observed for 1.2Hz excitation and the maximum displacements with PTMD are more than the maximum displacement of structure without PTMD, also increasing the mass ratio worsen the performance when $f_r=1.3$. When frequency ratio is 1, increasing the mass ratio helps in reducing the maximum displacement.

For 4Hz base excitation, the PTMD does not provide effective results and the maximum displacement of structure with PTMD for several combinations of parameters is more than the maximum displacement of structure without PTMD.

7. CONCLUSIONS

A 3 storied structure was tested for harmonic base excitations having frequency 1.2Hz and 4Hz. PTMD was provided on the structure having different parameters and different positions, the displacement of the structure was calculated from measured data and performance of PTMD in reducing the maximum displacement was determined and compared for different parameters. Following conclusions can be made from the observations.

1. The PTMD which is tuned for the specific frequency was particularly effective at lowering the response of the structure when the excitation is provided at that specific frequency.
2. PTMD suspended from the 3rd (top) floor produced the best results in lowering the displacement of the structure and avoiding resonance for 1.2Hz base excitation.

3. The effectiveness of PTMD on the second (middle) floor was inferior to that of PTMD on the top floor in minimizing the structural response. Furthermore, when PTMD was given a frequency ratio of 1.3, resonance of the structure was observed, and the maximum displacement of structure with PTMD was greater than the maximum displacement without PTMD.

4. When PTMD was provided on the 1st (bottom) floor, it was ineffective at reducing the response of the structure. Additionally, resonance of the structure was observed for a majority of parameter combinations, and the maximum displacement of structure with PTMD was much greater than the displacement of the structure without PTMD.

5. For 4Hz base excitation, PTMD located on top floor provides some reduction in the maximum displacement of the structure. PTMD located on 2nd floor and 1st floor have little to no effect in reducing the response for 4Hz excitation. And in some cases can increase the displacement of the structure.

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