An Experimental Investigation on Tuned Mass Damper for Mitigation of Structural Response of Frame Structures

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Abstract: - This research investigates the experimental study of Tuned Mass Damper (TMD) and its effect on frame models under sinusoidal excitation. To perform the shake table test, a frame model is developed and excited under sinusoidal loading to observe the structural response without and with a mass damper. Different parameters such as Frequency Ratio, Tuning Ratio, and Mass Ratio are considered during the study. The signal study is done both in the time domain and frequency domain. Under a particular range of excitation frequency, the behavior of TMD is studied by changing the mass ratio and tuning ratio. The efficiency of the TMD in terms of percentage reduction in displacement response is observed.

Keywords: - Sinusoidal Excitation, Mass Damper; Vibration, Mass Ratio, Tuning Ratio, Frequency Ratio.

1. INTRODUCTION

Currently, the scenario of an increase in population leads to a rise in space problems in urban areas. As a result, the number of flexible and tall buildings in the construction industry is increasing day by day. Therefore, these structures should be constructed to counteract the dynamic responses developed due to severe earthquake and wind motion by reducing the damping value.

Nowadays, different techniques have been adopted to control the structural response by providing strength, and flexibility and by using energy absorption methods which make the structures deform beyond their elastic limit. Various devices are used to suppress the vibration in structures which can be categorized into 4 types such as active, passive, semi-active, and hybrid. An external power source is used in active devices that operate control actuators to apply forces to the structures. The actuators send various signals which are created as a result of responses of the structure. Without the use of any external power source, passive devices impart forces that are developed in response to the motion of the structures. TMD is a type of passive device which connects to the primary structure like a secondary mass and under forceful excitation it absorbs the surplus energy developed in the primary structure. Semi-active devices are controllable passive control systems where the requirement of external energy is less as compared to active devices. Hybrid devices are a combination of active, passive, or semi-active devices to achieve a higher level of performance.

Till now, a lot of research work has been conducted to observe the efficiency of a Tuned Mass Damper in reducing the vibration of structures. The study on TMD was first initiated by Frahm in 1990 to reduce ship hull vibrations as well as the undulating motion of ships. Samali et al. in 2003 [6] & Chen and Wu in 2000 [3] studied the effectiveness of TMD on structures numerically by considering various factors. Wu et al. in 1999 [2], Ghosha and Basu in 2004 [4] investigated the behavior of soil structure interaction with TMD at various places. Nagashima et al. in 2001 observed the acceleration responses of high-rise buildings by attaching a hybrid mass damper (HMD) with bi-axial eccentricity and found it to be effective in reducing the structural response to 63 %.

Chen and Wu in 2004 studied both numerically and experimentally the effectiveness of many tuned mass dampers in reducing the vibration of the multi-story structure by identifying various dynamic properties. Kwok and Samali (2006) [8] conducted some experiments to test the effectiveness of both active and passive TMD and validated the results obtained with parametric studies which are used in the selection of the most favorable TMD parameters. Saidi et al.(2007)[9] examined some torsional coupled buildings under earthquake loadings and investigated the practical design issues of tuned mass dampers. They determined the best possible TMD system parameters by minimizing the mean square displacement response ratio on the top floor of buildings with and without TMDs.

Wong (2008)[10] numerically studied the dissipation of seismic energy in inelastic structures with tuned mass dampers. Lin et al.(2010) [11]studied the dynamic response control of structures using semi-active friction multiple-tuned mass dampers. Islam and Ahsan (2012) [12] optimized Tuned mass damper parameters using an evolutionary operation algorithm and determined the optimum parameters of TMD in reducing the top story response of the structure by using an evolutionary algorithm. They used the El Centro NS earthquake to develop a computer program and found a higher percentage of reduction on the roof of a ten-story structure using TMD with the application of EVOP. Kaveh et al. (2015) [14] used an optimization algorithm i.e., Charged System Search (CSS) to determine the optimum parameters of TMD to reduce the dynamic response of multi-story building systems under seismic excitations.

Kaveh et al. (2015) [15] developed a semi-active tuned mass damper to study the vibration of a 10-story building under four earthquake excitations and controlled the vibration by using a charged system search (CSS) algorithm and found that an optimized fuzzy controller performances better than a conventional fuzzy controller and a passive TMD. Qiong Wu et al. (2016) [17] experimentally studied the vibration of a 4-storey offshore building due to wind and earthquake and found that TMD can be effectively used to suppress the vibration. H Cetan and E. Aydin (2019) found that a correctly designed TMD can be effectively used in reducing vibrations. They have used a differential evolution algorithm to obtain the parameters such as mass, stiffness damping coefficient, etc.

Kaveh et al. (2020) [16] worked on the optimum design of a tuned mass damper inserter (TMDI) to study a 10-story base excited linear building under seismic excitations considering four different inherent damping values and minimizing the H∞ norm of the roof displacement transfer function. They found that the effectiveness of the TMDI decreased with increasing inherent damping of the structure. Kaveh et al. (2020) [19] established a robust optimum design of a Tuned Mass Damper by implementing the H2 and H∞ norm of the roof displacement transfer function which is compared to the objective functions under Near-Fault (NF) and Far-Fault (FF) earthquake motions. They also investigated the consequences of different characteristics of NF ground motions on the behavior of a benchmark 10-story controlled structure and found that the H∞ objective function is superior to the H2 objective function for TMD design. From the literature study, it can be observed that various numerical works have been done to learn the effectiveness of TMD to diminish the vibration of the structure. But, experimental investigations on this ground are relatively less.

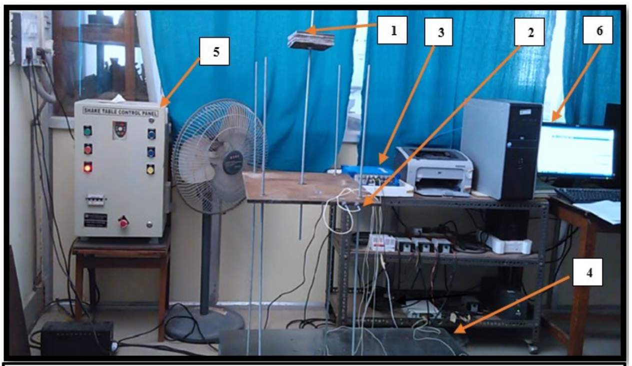
The purpose of the present work is to study experimentally the reduction in the structural response of a frame model subjected to sinusoidal excitation by attaching TMD and to study the effect of different parameters such as mass ratio, frequency ratio, tuning ratio, etc. on structural response. The mass ratio is defined as the ratio of the mass of the damper to the mass of the structure. Frequency ratio is defined as the ratio of excitation frequency to the natural frequency of the structure. The tuning ratio is defined as the ratio of the frequency of the damper to the natural frequency of the structure.

2. EXPERIMENTAL SETUP

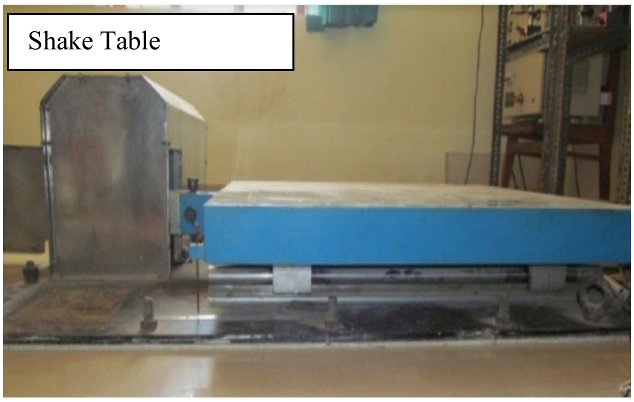
The laboratory equipment consists of (i) An unidirectional shaking table (ii) a Vibrating analyzer (iii) a Control panel (iv) an Accelerometer (v) a PC loaded with NV gate software (vi) a Frame model with and without secondary mass. Figure 1 shows the set-up of a single-story frame model on a unidirectional shake table of size 1mx 1m. The base of the table has a sliding perforated surface which is regulated by an induction motor. The perforations are positioned on a 100 x 100 mm network.

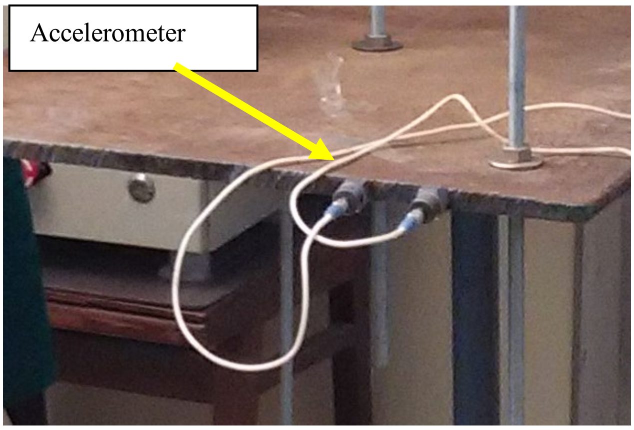
The unidirectional motion is imposed by a screw operated by the motor. The motor is driven by a power supply. The operating frequency range of the shake table is 0-20 Hz which is regulated from the control panel. The maximum payload of the shake table is 100 kg. The vibrating analyzer provides a solution in the form of structural testing equipment for vibration measurement and analysis. It helps in converting the electrical signal to a measured digital signal for analysis after which a variety of analyses and displays can be possible.

The most common processing on dynamic data is to perform FFT analysis to convert the data to the frequency domain from where most of the data can be viewed. Thus, it provides a fast, easy, and accurate way to use time and frequency domain measurements for structural tests. Accelerometers are attached to the frame at the location where the acceleration needs to be measured. The other end of an accelerometer is attached to the vibrating analyzer which converts the electrical signal into a digital signal. Further, the data can be transformed to determine the displacement by software known as NV gate loaded in PC. It has the provision to get the velocity and displacement response by integrating the acceleration data. The roof of the frame model developed for the experiment is a rectangular iron plate supported by four columns of circular cross-section. The columns are rigidly supported on the table with the help of bolts. So, during the experiment, the supports are assumed to be fixed. TMD is formed by various small square plates of size 126 x 126 mm and attached at the middle of the roof.



1. Mass Damper 2. Accelerometer 3. Vibrating Analyzer
4. Shaking Table 5. Control Panel 6. PC loaded with NV GATE





3. RESULTS ANALYSIS

Free vibration analysis is done to find out the natural frequency of the frame model without attaching TMD as shown in Figure 2 which shows the displacement and acceleration plots. The damping ratio calculated analytically from the free vibration analysis is found to be 0.003. By attaching an accelerometer to the roof, an FFT plot as shown in Figure 3 is obtained from which the fundamental frequency of the model is found to be 1.75 Hz. The various parameters such as lateral stiffness, Moment of inertia of the frame, etc. are obtained analytically and tabulated in Table 1.

Table 1. Experimental Parameters

Description	Values
Dimension of frame roof	500 mm x 400 mm
Mass of frame roof	15.44 kg
Column height	70 cm
Column diameter	7.7 mm
Fundamental/Natural frequency of the frame (f_n)	1.75 Hz
Damping ratio(ζ)	0.003
Frame stiffness(k_f=m ω^2)	1864.84 N/m
Column stiffness(k= $k_f/4$)	466.62 N/m
Moment of inertia of column	$1.7\times 10^{-10} m^4$
Elasticity modulus of frame	$7.8 \times 10^{10} \frac{N}{m^2}$

Figure 1. Experimental setup

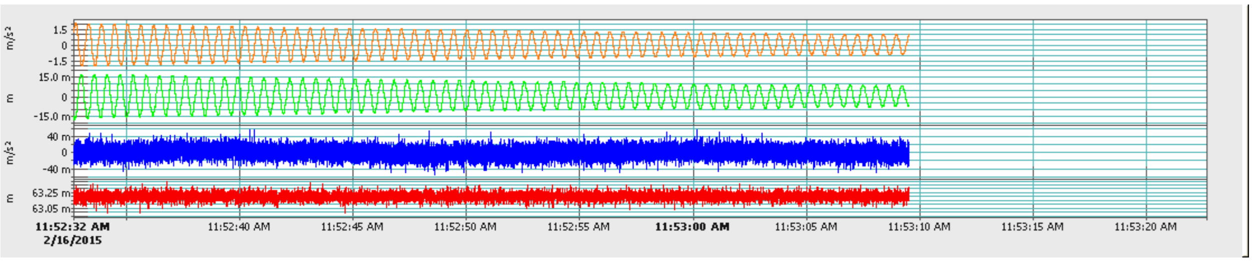


Figure 2. Time History Plot under Free vibration

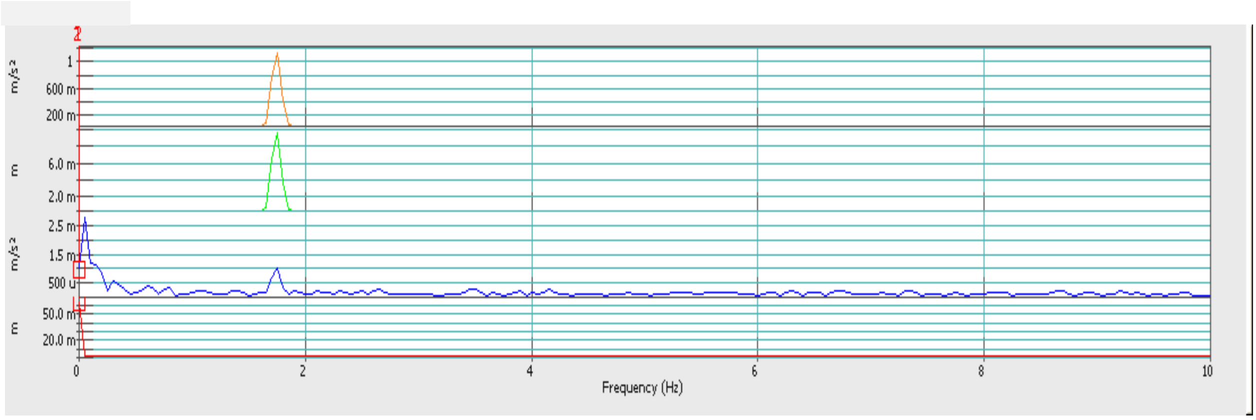


Figure 3. Free vibration analysis to obtain natural frequency of the frame

3.1 Effect of frequency ratio on structural response without mass damper

Frequency ratio is defined as the ratio of excitation frequency to the natural frequency of the structure. During force vibration analysis, the frame model is excited by a sinusoidal loading with excitation frequency ranging from 0.18 Hz to 2.97 Hz is expressed by the equation,

$$x = x_0 \omega^2 \sin(\omega t) \tag{1}$$

$$\omega = 2\pi f \tag{2}$$

where, x_0: amplitude of excitation = 0.5 cm
f: excitation frequency

Maximum structural responses obtained from the time history plots using NV GATE software at different forcing frequencies are plotted against the frequency ratios. The experimental setup for a single-story frame model with mass damper is depicted in Figure.1

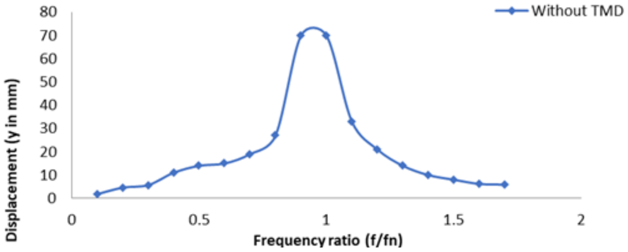


Figure 4. Displacement response of the frame model at various frequency ratios

Figure 4 shows an increase in the maximum structural response of the frame model (without mass damper) with an increase in forcing frequency till the state of resonance (f=fn=1.75 Hz) is reached. The maximum displacement is found to be 70 mm at the point of resonance and after that again reduction in response occurs with a further increase in excitation frequency.

3.2 Effect of tuning ratio on structural response with Mass Damper

The tuning ratio is defined as the ratio of the frequency of the damper to the natural frequency of the structure. A secondary mass (damper) of weight 0.15 times the weight of the primary frame is taken at the center of the frame as shown in Figure 5. At a constant mass ratio of 0.15, to observe the effect of tuning ratio, the damper frequency (fd) is changed by changing the length of the rod to which the damper is attached. The length of the damper (L) in cm taken at tuning ratios of 0.8, 1.0 & 1.3 are 60, 52.44 & 44.23 respectively.

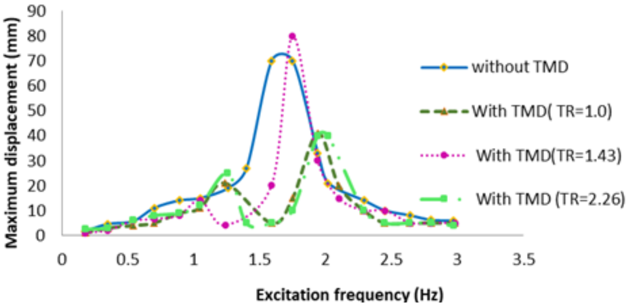


Figure 5. Displacement response of the frame model at various tuning ratios at a mass ratio of 0.15

Two different peak points corresponding to two modal frequencies are observed in the Figure. 6 after attaching a secondary mass to the primary frame model. At a lower exciting frequency, the height of the peak point is lower than that obtained at a higher exciting frequency. Because at lower exciting frequencies, flexible structures are more affected than rigid structures and vice versa. So, at a lower exciting frequency, the damper being flexible moves faster than the frame thus reducing the structural response of the new frame. Similarly, at higher exciting frequencies, the frame being rigid moves faster than the damper.

After attaching the damper mass, the maximum reduction in structural response occurs at the resonance point, when the exciting frequency becomes nearly equal to the fundamental frequency of the frame model. It can also be observed that this response reduction is greater when the damper is tuned to the fundamental frequency of the frame i.e., when the tuning ratio is close to unity. With an increase or decrease in the tuning ratio, the response is going on increasing.

Hence, to obtain the most favorable response, the fundamental frequency of the damper is always tuned to the fundamental frequency of the primary structure such that when that frequency of the structure gets excited, the damper will vibrate out of phase with the structural movement. The surplus energy developed in the primary structure is transmitted to the damper and dissipated due to relative motion developed between them at a later stage.

3.3. Effect of mass ratio on structural response with Tuned Mass Damper

Different mass ratios, which is the ratio of damper mass to frame mass, varying from 0.1 to 0.25 are considered and the corresponding displacement responses are observed both in the time domain and frequency domain. Each time the damper is tuned to the natural frequency of the frame by changing the damper length.

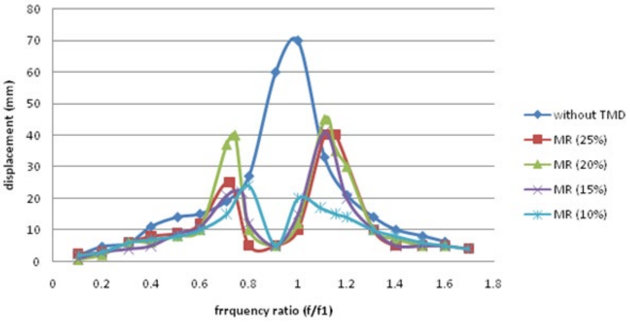


Figure 6. Displacement response of structure for varying frequency ratios with different mass ratio

The experimental parameters of the single-story frame model with TMD have been presented in Table 2. The effect of mass ratio can be observed in Figure 6.

Table 2. Experimental parameters of single-storey frame model with TMD

Mass Ratio (m_d/m)	Mass of damper (m_d) (kg)	Damper stiffness (k_d) (N/m)	Length of damper (L_d) (cm)	Frequency (Hz)	
				First mode (f_{n1})	Second mode (f_{n2})
0.10	1.544	183.83	60	1.4	1.9
0.15	2.316	275.74	52.44	1.35	1.95
0.20	3.088	367.65	47.65	1.3	2.0
0.25	3.860	459.57	44.23	1.25	2.0

m_d=Mass of the damper, m=Mass of the frame

3.4 Effect of mass ratio by Time-domain analysis

From time-domain plots, the maximum structural responses for each forcing frequency varying from 0.18 -2.97 Hz are noted. Figures 8(a), 8(b), 9(a), and 9(b) show the comparative study of displacement and acceleration time history signal of the frame without and with TMD at various mass ratios for a frequency ratio of 0.8 and 1.0.

At a frequency ratio of 0.8, the maximum displacement and acceleration response of the frame without TMD is found to be 26 mm and 2.1 m/s2 respectively. With the increase in mass ratio from 0.10 to 0.25, the response is reducing gradually. At the point of resonance i.e., at a frequency ratio of 1, maximum displacement and acceleration response of the frame without TMD is found to be 70 mm and 8 m/s^2 respectively.

After attaching the TMD, there is an abrupt reduction in structural response at various mass ratios. At a mass ratio of 0.25, the value of maximum displacement and acceleration is found to be 10 mm and 1 m/s2 respectively. Thus, after attaching TMD, optimum reduction in response is observed at the point of resonance irrespective of the mass ratios taken.

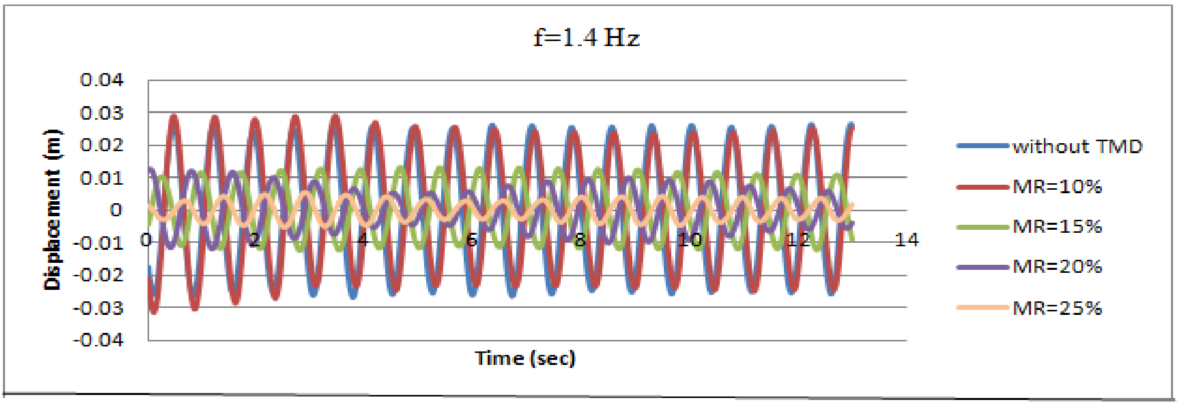


Figure 7(a). Time histories of Structural displacement responses at frequency ratio = 0.8

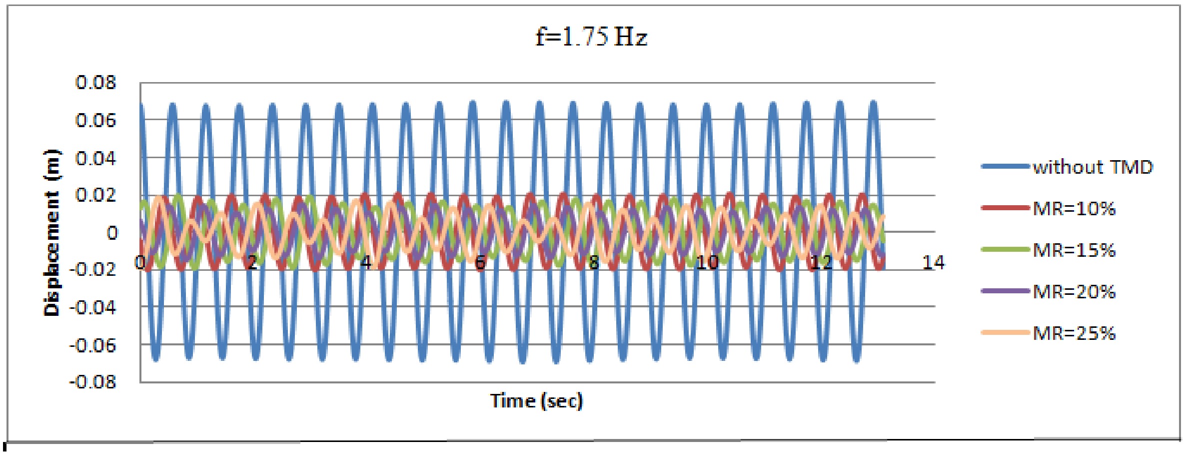


Figure 7(b). Time histories of Structural displacement responses at frequency ratio = 1.0

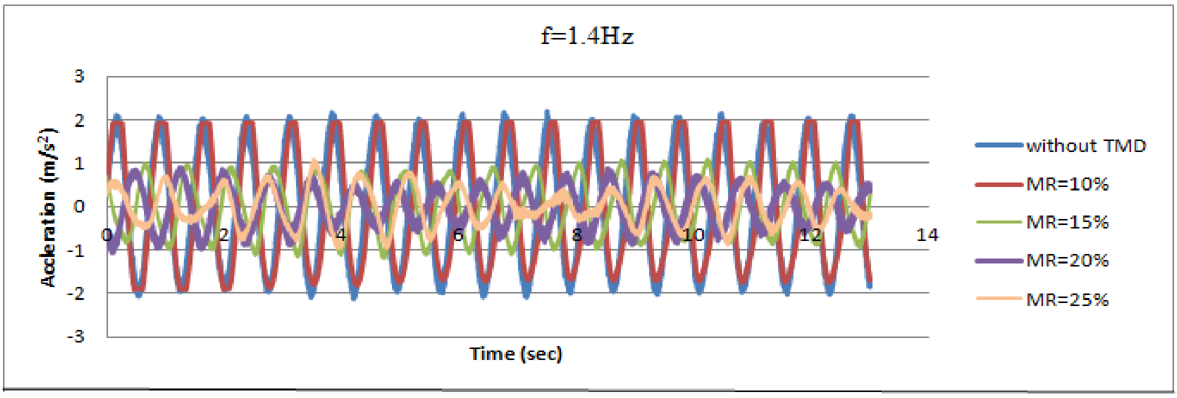


Figure 8(a). Time histories of Structural Acceleration responses at frequency ratio = 0.8

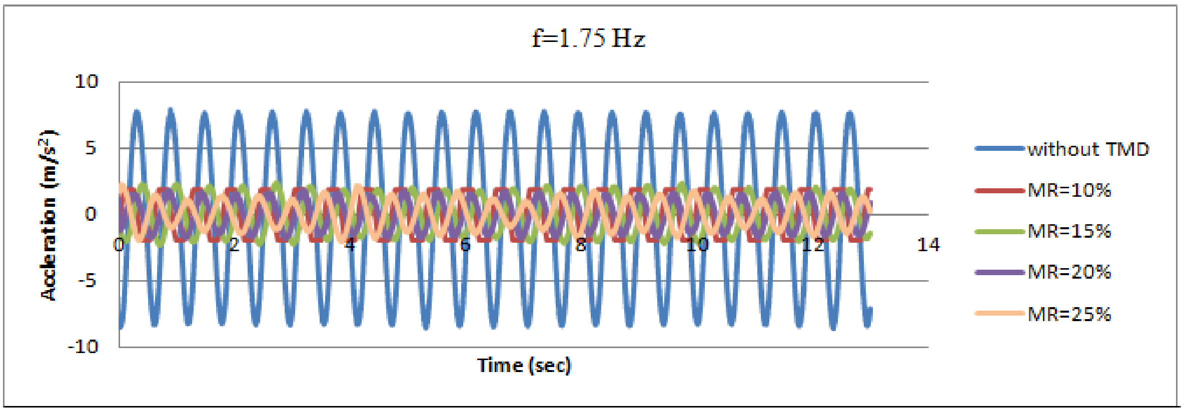


Figure 8(b). Time histories of Structural Acceleration responses at frequency ratio=1.0

3.5 Effect of mass ratio by Frequency domain analysis

From figures 9 to 12, it is observed that the percentage reduction in displacement response is found to be 71.4, 78.6, 82.8, and 85.7 corresponding to the mass ratios of 0.1, 0.15, 0.2, and 0.25 respectively. In all four cases, the maximum reduction in structural response occurs at the point of resonance and this reduction increases with an increase in mass ratio. From Figure 13 it can be observed that the distance between two peak points after attaching TMD to the frame is increasing initially with an increase in mass ratio and then remain constant.

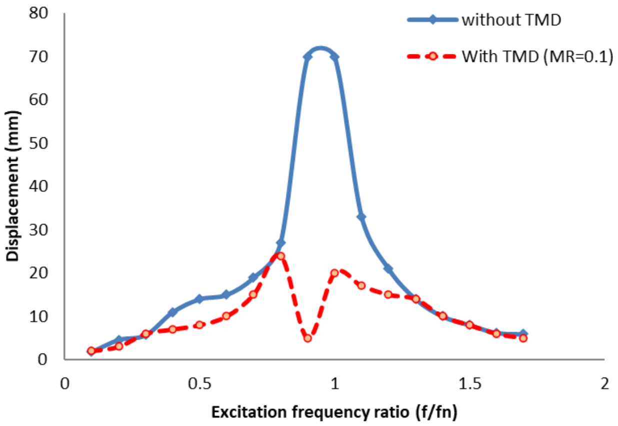


Figure 9. Displacement response of the frame model at various mass ratios of 0.10

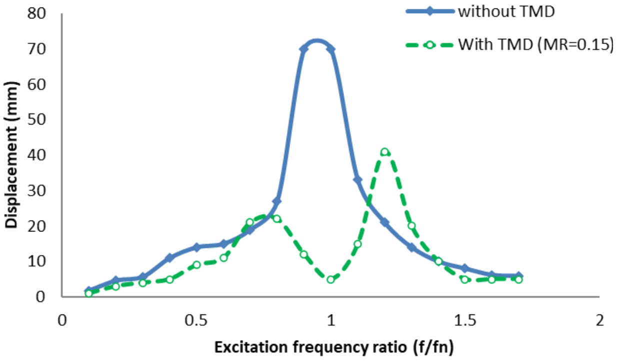


Figure 10. Displacement response of the frame model at various mass ratios of 0.15

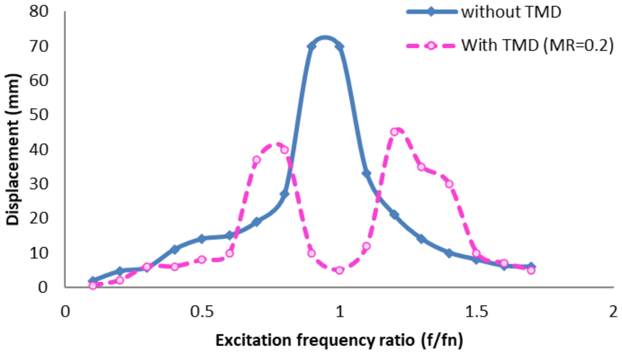


Figure 11. Displacement response of the frame model at various mass ratios of 0.20

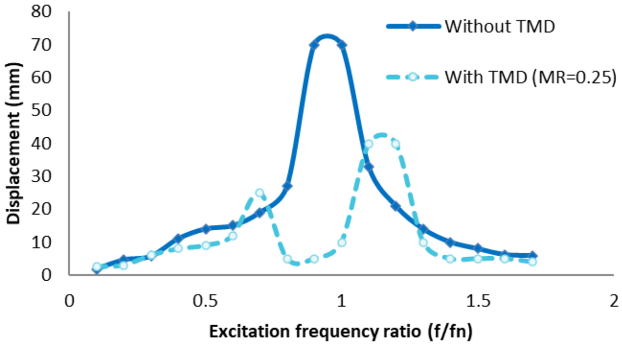


Figure 12. Displacement response of the frame model at various mass ratios of 0.25

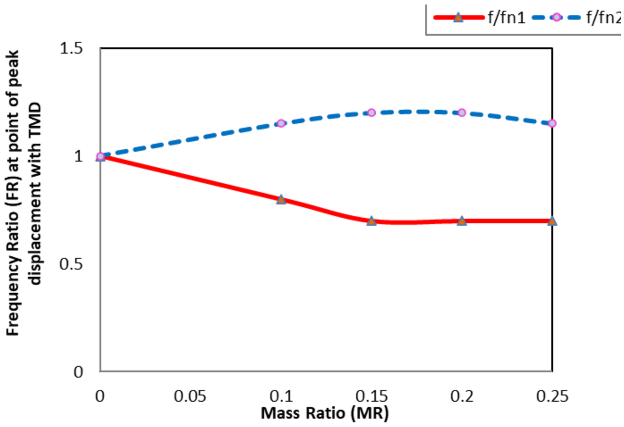


Figure 13. Variation in distance between two peaks with TMD at different Mass ratios

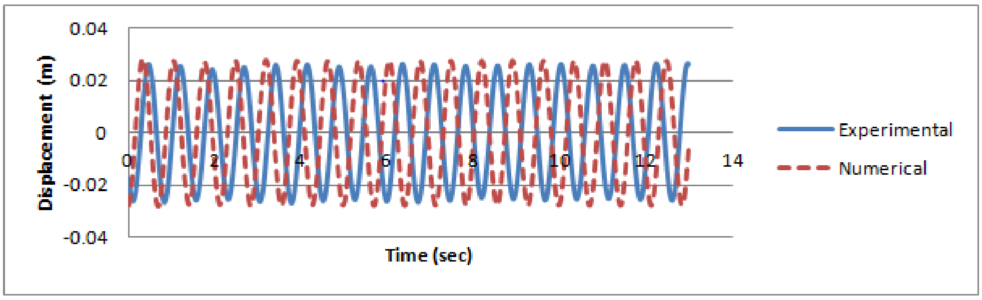


Figure 14. Comparison of numerical and measured structure displacement time history response without TMD for frequency ratio=0.8

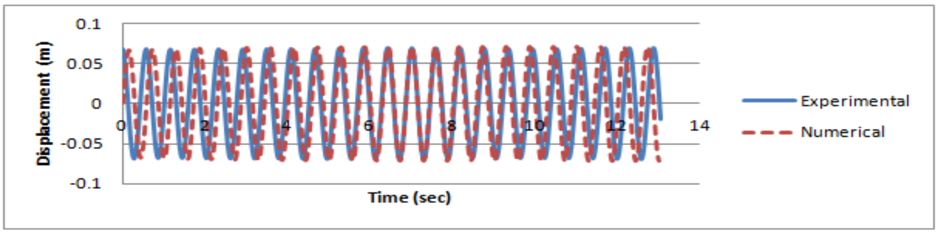


Figure 15. Comparison of numerical and measured structural displacement time history response without TMD for frequency ratio=1.0

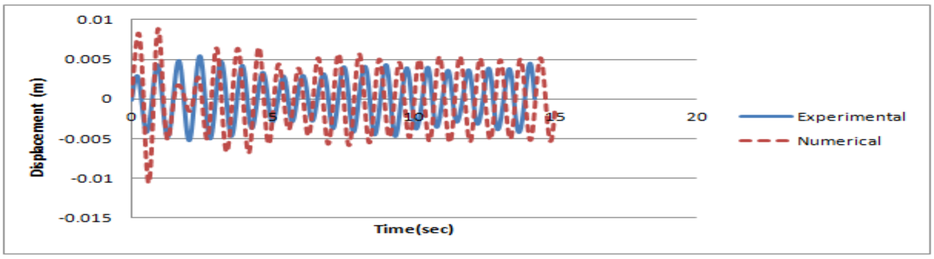


Figure 16. Comparison of numerical and measured structural displacement time history response with TMD for frequency ratio=0.8

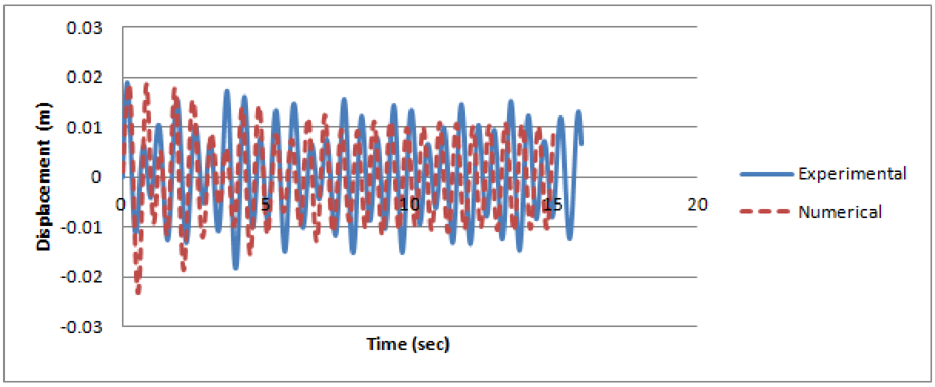


Figure 17. Comparison of numerical and measured structural displacement time history response with TMD for frequency ratio=1.0

3.6. Numerical validation:

The displacement time history response of the frame subjected to sinusoidal base excitation obtained experimentally is validated using the numerical finite element method. The results obtained with and without TMD for a frequency ratio of 0.8 and 1 are presented in Figures 14 to 18. It shows that both the results are in very close agreement.

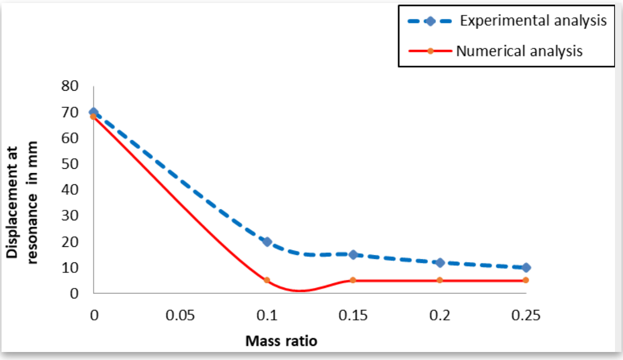


Figure 18. comparison of experimental and numerical results during resonance at various mass ratios

4. CONCLUSION

This experimental investigation concludes the potentiality of the tuned mass damper in the reduction of dynamic response. A set of experiments were conducted to examine the effectiveness of a damper under sinusoidal excitation. Various forcing frequency ratios ranging from 0.1-1.7 and different mass ratios ranging from 0.1 -0.25 were considered. The study revealed the maximum structural response at the resonance point ($f=f_n$) without mass damper. After attaching the mass damper at the center of the frame roof, for the given range of frequency ratio, two peaks were observed corresponding to two natural frequencies of the new structure, and maximum reduction in response occurred at the point of resonance. The effect of the tuning ratio is also studied. At the tuned condition i.e., when the damper was tuned to the natural frequency of the primary frame model (fd=fn), response reduction was found to be maximum. With the increase in mass ratio, the response reduction was increased at the resonance point. The experimental results were successfully validated analytically. From the study, it has been concluded that a properly designed mass damper considering various parameters such as frequency ratio, tuning ratio, and mass ratio is found to be very effective in reducing the structural response of frames. However, as dampers are useful in reducing the response in high-rise buildings, a further study can be made by considering a multi-storey frame model.

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