AN EXPERIMENTAL STUDY ON MTMD TO IMPROVE STRUCTURAL PERFORMANCE UNDER DYNAMIC LOADING

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ABSTRACT :

Studies confirmed that using optimum parameters (mass ratio, damping ratio, and frequency range), MTMD can improve structural performance under dynamic loading. This study aimed to better understand the behavior of structural system with MTMD experimentally, and verify numerical approaches. Two scaled models were used in the experimental study, a SDOF and a 3-DOF system. The models represent regular structures with dominant first mode. MTMD were then attached to the main structures, with the total mass ratio of approximately ten percent of the story mass. Three different numbers of TMD were used, i.e. 1TMD, 3TMD, and 5TMD. For MDOF structure, the locations and distributions of MTMD were also varied from. The models without any TMD were used as a benchmark model to evaluate the effectiveness of MTMD. Prior to experimental studies, identification procedures were carried out to each structural model and dampers to determine the dynamic properties. The experimental study was conducted using shake table with harmonic motions. The responses were recorded using accelerometers and LVDT. The results show that MTMD can reduce the maximum displacement of structures under harmonic motions, thus confirming numerical results. Having MTMD instead of TMD also increased the robustness of the systems, demonstrated by the reduction of structural responses for various input motions. It should be noted that for most cases, using all MTMD located on the top story produced best results compared to other placements or distributions.

KEYWORDS: Multiple tuned mass dampers, experimental study, benchmark model, passive control, dynamic load.

1. INTRODUCTION

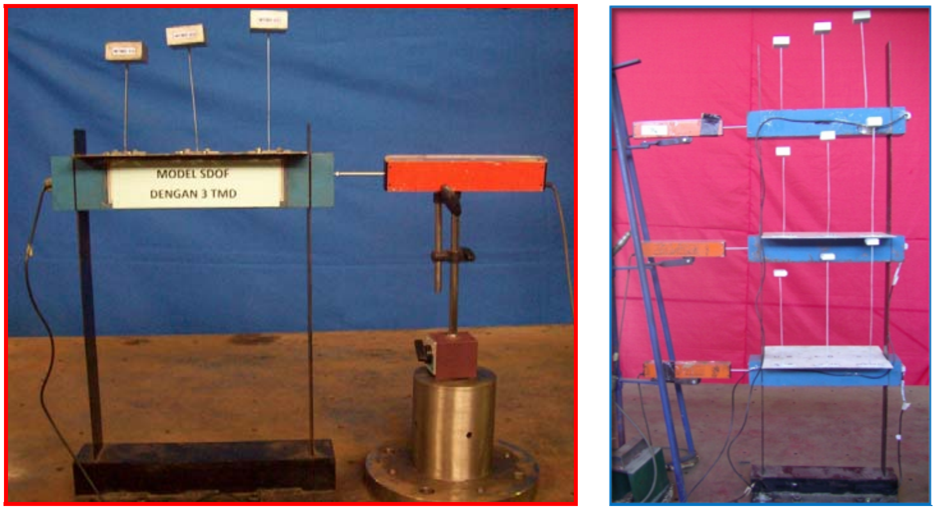
The behavior of structures subjected to dynamic loads is more difficult to predict due to the complexity of the problems. Analysis can be very complicated and usually requires sophisticated tools. Controlling the structural responses under dynamic loading has been an objective to many researches. Various approaches have been developed to control or reduce the structural responses under dynamic loads. One of the devices used for controlling dynamic response is Multiple Tuned Mass Dampers (MTMD), which can be modeled as several additional masses attached to the main structure.

Studies revealed that the performance of MTMD system is determined by its parameters, i.e. mass ratio, damping ratio, frequency range (defined as half of the range between the lowest frequency and the highest frequency of TMD), locations, and distributions. Using an optimum combination of parameters, MTMD can effectively improve structural performance under dynamic loading (Rana and Soong, 1998; Soong and Dargush, 1997; Abe and Igusa, 1995; Kusumastuti and Rildova, 2006). Most of these studies were conducted numerically to obtain the effectiveness of MTMD system. Few experimental studies were conducted on the subject to validate the numerical models. Therefore, this experimental study aimed to better understand the behavior of structural system with MTMD, as well as to verify the numerical approaches.

2. EXPERIMENTAL MODELS

Two physical models were used in the study, a SDOF and a 3-DOF system, which were approximately of one tenth scale (about 30 cm height for SDOF and 100 cm height for 3DOF), and were designed within the limitations of the testing facilities at the Structural Mechanics Laboratory, Inter University Center, ITB.

The models were 2D steel structures and constructed such that they acted as shear buildings with only one translational movement occurred. The columns were made of steel plate, and the beams acted as the story masses were made of steel blocks, thus limiting the movement laterally in the beam longitudinal axis. The models were designed to be versatile with removable parts and easy access for energy dissipation devices. The story masses are similar, and they can be adjusted along the height of the main columns. The models without any dampers were used as the benchmark models. For structures with MTMD or TMD, dampers were attached to the floor masses using additional trays fastened to the floor masses. Figure 1 shows the structural models used in the experiments.



(a) (b)

Figure 1 Physical models of (a) SDOF structure and (b) 3DOF structure.

Each damper used for TMD and MTMD system was modeled and constructed as an SDOF system. The total mass ratio of a TMD/MTMD system was approximately 10 percent of the story mass of the model. Three different numbers of TMDs were used for each structural model, i.e. 1TMD, 3TMD, and 5TMD. Tuning of the damper frequencies were done using Den Hartog's solution, with the middle frequency of the damper in MTMD system was 0.9 of the frequency of the structure (Den Hartog, 1984). For 3DOF structure, locations and distributions of MTMD were also varied in addition to variation of the number of TMDs. Figure 2 shows all dampers used for TMD and MTMD systems in the experimental work.

Figure 2 Dampers used for TMD and MTMD.

Using variations of structural models and dampers, 18 configurations of structural system with MTMD were obtained. They include 4 SDOF models and 14 MDOF models, and illustrated in Figure 3.

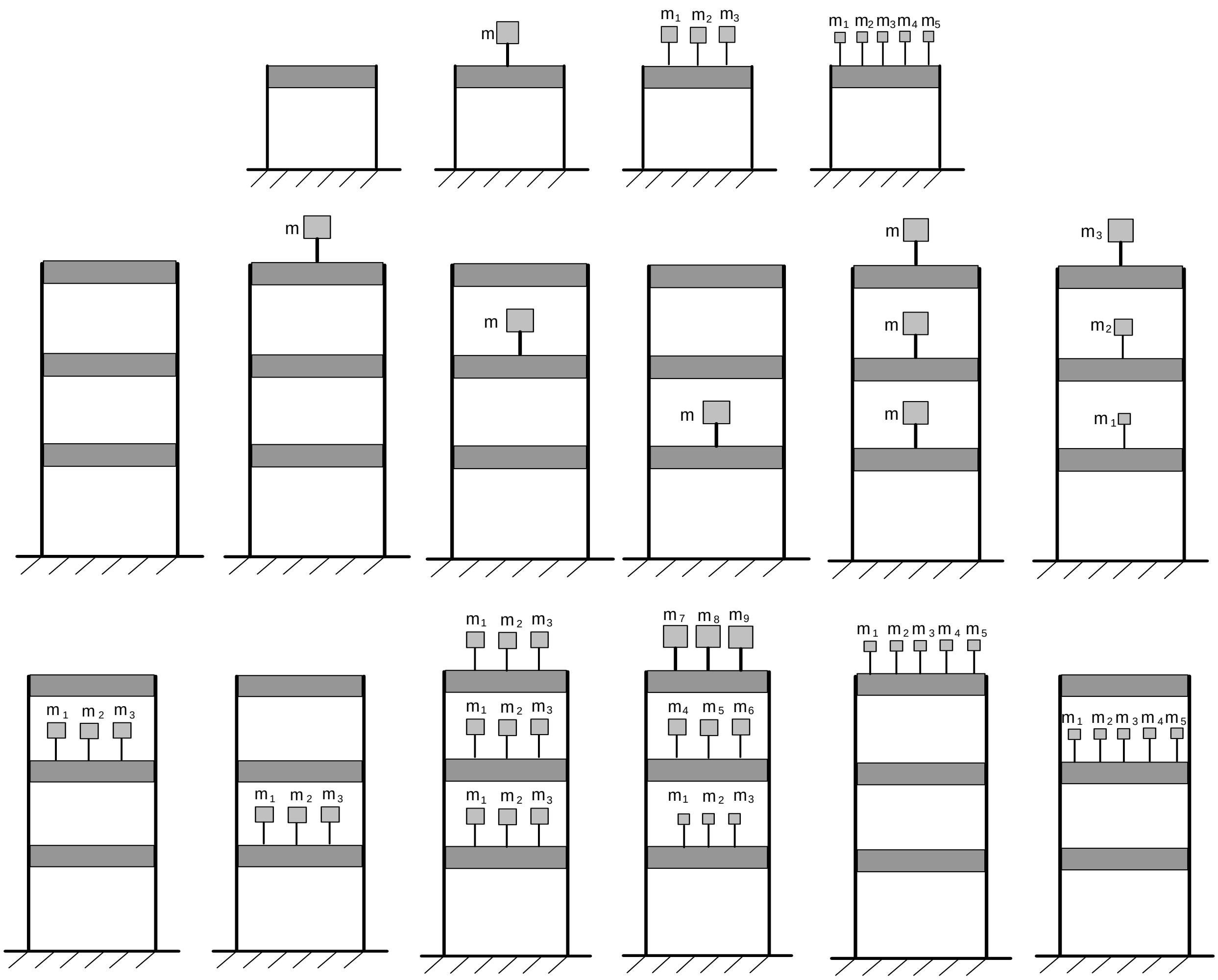


Figure 3 Variations of structural systems with MTMD.

The models were then placed on top of the shake table The test set up for both models are given in Figures 4 and 5. The responses were recorded using accelerometers and LVDT. A series of harmonic motions in terms of sinusoidal were then selected to be used as dynamic loadings for the models. The selection for the input motions was based on the structural properties and the shake table characteristics and limitations.

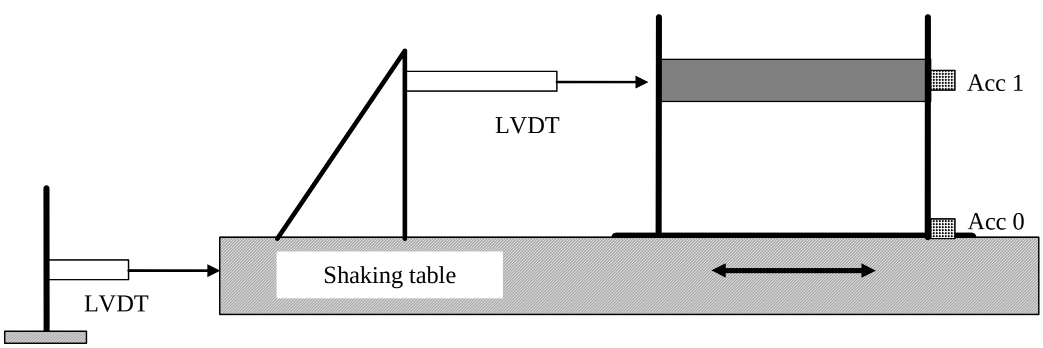


Figure 4 Test set-up of SDOF model.

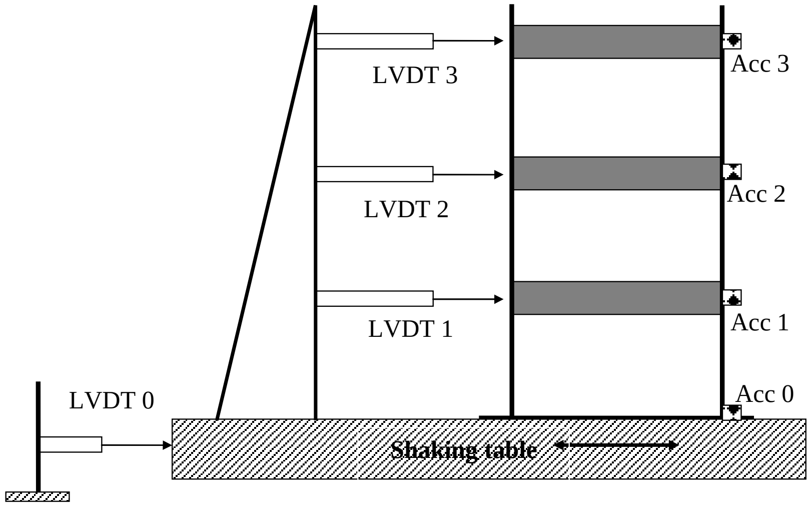


Figure 5 Test set-up of 3DOF model.

3. EXPERIMENTAL RESULTS

Prior to conducting experimental studies with harmonic motions, identification procedures were carried out for each structural model and the TMDs to determine their dynamic properties using free vibration tests. Accelerograms were obtained and by utilizing Fast Fourier Transform to produce the Transfer Functions, the frequencies, mode shapes, stiffness, and damping characteristics were calculated. The results show that the predominant periods of SDOF and 3DOF structures are approximately 0.37 sec. and 0.61 sec., respectively. The periods of the dampers were found close to the designed periods.

Dynamic loads were then applied to the structure in terms of sinusoidal displacement time histories. The maximum displacement of the shake table ranged from 2 percent to 6 percent of the maximum stroke, while the frequencies of the input motion were varied from 1 Hz. to 5 Hz. with 0.5 Hz. increments. Responses were measured using Dynamic Magnification Factor (DMF) which is the ratio of maximum roof displacement of structures with dampers to the maximum roof displacement of structures without. Dampers. The smaller DMF values are, the more effective dampers reduced structural responses.

Table 1 shows results for SDOF structures with 2 percent maximum stroke of the shake table. Both TMD and MTMD seem to be sensitive to tuning, shown from large DMF values. For input frequency that is close to the natural frequency of the structure, resonance was apparent and could not be countered with dampers. Results from SDOF structure were used to refine the 3DOF models and dampers used with these models.

Table 1 Results of experiments on SDOF model.

Input Frequency	1TMD			3TMD			5TMD		
	Maximum Displacement(mm)		DMF	Maximum Displacement(mm)		DMF	Maximum Displacement(mm)		DMF
	1TMD	No TMD		3TMD	No TMD		5TMD	No TMD	
1	0.8	1.2	0.67	2.2	1.4	1.57	1.8	1.4	1.29
2	2	5.6	0.36	5.8	4.8	1.21	12.2	4.4	2.77
3	10.8	9.8	1.10	6.8	21.2	0.32	41.4	56	0.74
4	6.8	7.2	0.94	8.8	9.6	0.92	9.6	9.2	1.04
5	6.4	6.4	1.00	7.2	7	1.03	7	6.8	1.03

Table 2 present results for experiments with 3DOF structures by varying the number of dampers, the location of MTMD system, and the distribution of MTMD system. Some of tests scheduled were unable to conduct due to large displacement of structural models.

Table 2 Results of experiments on 3DOF model.

Table stroke amplitude (mm)	Input Frequency (Hz)	DMF							
		Number of dampers			Location of MTMD			Distribution of MTMD	
		1 TMD	3TMD	5TMD	3TMD at 3rd Floor	3TMD at 2nd Floor	3TMD at 1st Floor	Triangular	Uniform
1	1	0.53	0.71	0.82	0.71	1.21	0.77	1.78	1.08
	1.5	0.45	0.87	0.75	0.87	0.85	0.89	0.92	1.64
	2	1.08	1.19	0.78	1.19	1.26	1.27	0.82	0.99
	2.5	1.15	1.05	0.68	1.05	0.94	0.97	1.17	1.21
	3	0.97	1.06	0.67	1.06	1.07	1.09	1.14	1.13
	3.5	0.95	1.02	0.69	1.02	0.94	0.88	1.03	1.10
	4	1.20	1.13	-	1.13	0.94	0.95	1.14	1.18
	4.5	0.99	0.91	0.52	0.91	0.96	0.96	0.57	0.55
	5	1.10	0.92	0.49	0.92	0.96	1.12	0.76	0.81
1.5	1	0.96	0.97	0.89	0.97	0.82	1.09	1.08	1.20
	1.5	0.36	0.77	0.63	0.77	0.89	0.97	0.79	1.11
	2	1.15	1.18	0.69	1.18	1.06	1.10	0.92	0.87
	2.5	1.10	0.99	0.70	0.99	0.88	0.94	1.03	0.98
	3	1.26	1.07	0.71	1.07	0.93	1.02	0.90	0.97
	3.5	1.11	0.92	0.77	0.92	0.93	0.83	1.10	1.06
	4	1.04	0.92	-	0.92	0.92	0.96	1.47	1.50
	4.5	0.95	1.02	0.60	1.02	1.00	1.06	0.75	0.71
	5	0.87	0.96	0.65	0.96	0.96	1.14	0.88	0.85
2	1	-	0.98	0.96	0.98	0.68	1.00	0.96	1.09
	1.5	-	0.87	0.72	0.87	0.66	1.04	1.11	1.15
	2	-	1.07	0.83	1.07	0.76	1.03	0.94	0.88
	2.5	-	0.98	0.82	0.98	0.74	0.94	0.96	0.96
	3	-	1.00	0.78	1.00	0.79	1.09	0.94	0.96
	3.5	-	0.97	0.79	0.97	0.90	0.89	1.03	1.05
	4	-	1.10	-	1.10	1.00	1.06	1.42	1.41
	4.5	-	1.06	0.69	1.06	1.16	1.07	0.73	0.72
	5	-	0.94	0.65	0.94	1.02	1.03	0.91	0.96
2.5	1	-	0.99	0.91	0.99	1.04	1.00	1.21	1.20
	1.5	-	-	0.67	-	-	-	1.05	1.12
	2	-	1.10	0.84	1.10	1.06	1.01	0.99	0.90
	2.5	-	0.96	0.86	0.96	0.96	1.04	0.98	1.01
	3	-	1.01	0.86	1.01	1.11	1.10	1.02	1.02
	3.5	-	1.02	0.86	1.02	0.95	0.92	1.02	0.99
	4	-	1.06	-	1.06	1.04	0.94	1.30	1.36
	4.5	-	0.91	0.72	0.91	1.01	0.96	-	-
	5	-	1.01	0.72	1.01	1.03	0.95	0.46	0.50
3	1	-	0.92	0.92	0.92	1.03	-	1.16	1.06
	1.5	-	-	0.54	-	-	-	-	1.15
	2	-	1.03	0.90	1.03	1.03	0.92	0.99	0.95
	2.5	-	1.05	0.89	1.05	0.99	0.98	0.99	0.96
	3	-	1.01	0.92	1.01	1.01	0.96	1.08	1.03
	3.5	-	0.95	0.83	0.95	0.87	0.88	1.08	1.08
	4	-	0.98	-	0.98	1.01	0.95	1.34	1.33
	4.5	-	1.06	0.74	1.06	0.96	0.98	-	-
	5		0.99	0.85	0.99	1.05	0.96	0.48	0.45

The experimental results reveal that MTMD can reduce the maximum displacement of structures under harmonic motions. The effectiveness of MTMD varies, depending on the parameters of MTMD, structural properties, and the input frequencies. Using 5TMDs seems to produce best results, while in general, having MTMD instead of TMD also increased the robustness of the systems, demonstrated by the reduction of structural responses for various input motions. Variation of location and distribution revealed that placing all TMDs at the top floor give maximum reduction in structural response.

4. EXPERIMENTAL VS NUMERICAL RESULTS

Numerical models were developed for SDOF and 3DOF structures based on the experimental study. Figure 5 shows the results from both experimental and numerical studies of SDOF structure with various numbers of dampers. The numerical analysis was able to estimate the experimental studies, although minor discrepancies still occurred due to imperfections of the models. The structural response at input frequency of 2 Hz for 3TMD and 5TMD seem to be high due to resonance with the frequency of SDOF structure with 5TMD, while 1TMD which was tuned to the frequency of the structure worked very well to avoid this problem. For other input frequencies, MTMD was as effective as TMD, if not slightly better.

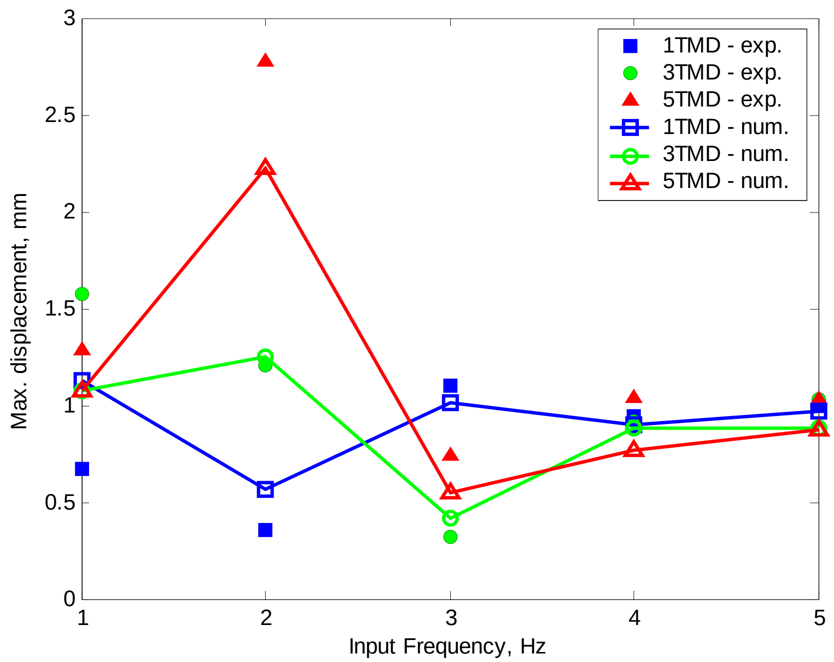


Figure 6 Comparison of experimental and numerical results for SDOF structure with 1TMD, 3TMD, and 5TMD.

Results for 3DOF models show that the comparison between numerical and experimental studies is not as good as SDOF model. Figure 7 shows that while numerical analysis predicted that MTMD system can reduce the maximum top floor displacements, the experimental study found that the response of systems with MTMD was much higher. Various imperfections in the experimental model are likely to contribute to the discrepancies. For example, the frequencies of dampers in the experimental model were not evenly spaced as in the numerical one. Also, the connections of the structural system and dampers were prone to movements of the table. The shaking might have unfastened the bolts on these connections. However, in the case where the input frequencies were very close to the frequencies of the structure, MTMD systems were able to reduce the structural response. With more than one DOF, MTMD systems were able to control the response for the first mode or higher.

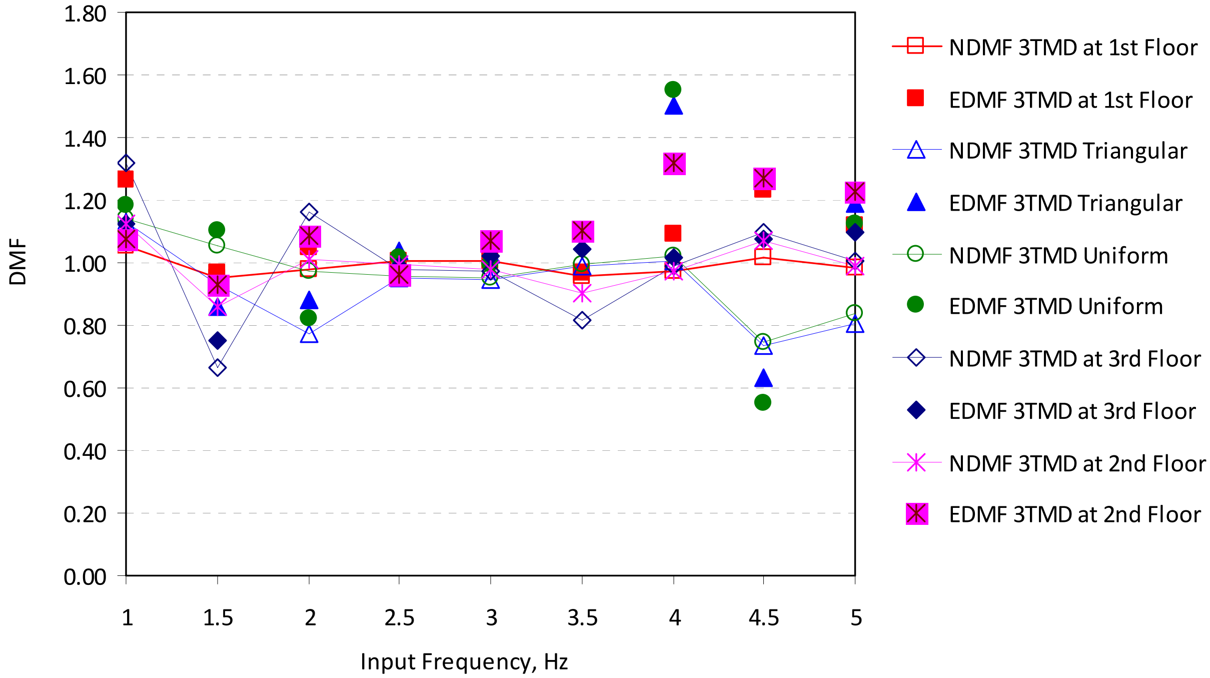


Figure 7 Comparison of experimental and numerical results for 3DOF structures.

4. CONCLUSIONS

MTMD has been introduced as a device used to control dynamic responses of structures. Studies confirmed that using optimum combination of its parameters (mass ratio, damping ratio, and frequency range), MTMD can effectively improve structural performance under random dynamic loading. Therefore, an experimental study was conducted to better understand the behavior of structural system with MTMD, as well as a verification of numerical approaches.

Two scaled structural steel models were used in the experimental study, a SDOF and a 3-DOF system, designed such that these models acted as shear buildings with one translational movement. The models without any TMD attached were also used as a benchmark model. For structural systems with MTMD, MTMD were attached to the main structures and the total mass ratio of MTMD system was taken as approximately ten percent of the story mass of the model. Three different numbers of TMD were used, i.e. 1TMD, 3TMD, and 5TMD. For MDOF structure, the locations of TMD were also varied from the first story to the third story, with different distribution of MTMD mass ratio on each floor. Identification procedures were carried out to each structural model and the TMDs to determine their dynamic properties. The models were then placed on top of a shake table and subjected to harmonic motions, and the structural responses for models with MTMD were then compared to the models without MTMD.

Experimental studies revealed that MTMD was able to control structural responses, and the effectiveness of the system is comparable to TMD system. In the case of mistuning, MTMD was able to overcome this problem, thus confirming numerical results. Having MTMD instead of TMD also increased the robustness of the systems, demonstrated by the reduction of structural responses for various input motions. Numerical and experimental results are comparable, especially for SDOF structure. For 3 DOF model, the agreement between numerical and experimental models is not as good as expected, due to imperfections found in the physical model. Further studies need to be conducted to analyze and model the imperfections and include them in numerical analysis. It should be noted that both experimental and numerical studies reveal that for most cases, using all MTMD located on the top story produced best results compared to other placements or distributions.

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