Experimental Study on the Efficiency of Passive Auto-Tuning Compound Pendulum Mass Damper

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DOI: https://doi.org/10.63990/zede.v43i.12970

ABSTRACT

A Tuned Mass Damper (TMD) is a device used to reduce the effects of dynamic responses of a structure during seismic action. In this study, a test model of a two-story steel structure was used to evaluate the efficiency of the Passive Auto-Tuning Compound Pendulum Mass Damper (PATCPMD). The PATCPMDs were suspended in the structure's top and lower stories and controlled by a group of flexible ropes that formed a compound pendulum, but it was not quite a compound pendulum and could move in any translational direction. The results showed that use of PATCPMD can provide significant control over the structure's translational, torsional, and coupled vibrations, with a maximum reduction in peak SSMS of 75 % for translational vibrations and up to 65 % for torsional vibrations when they are suspended in the first story. These values increased to 90 % for translational and 87 % for torsional vibrations when suspending in the second story. For forced vibrations, the maximum reductions in vibration control achieved were 68 % and 89 % if the damper was suspended in the first and second floor levels, respectively. Results showed that using PATCMD is more efficient when suspended on the second floor.

Keywords: Coupled vibrations, Steel structure, PATCPMD, Torsion, Translation,

1. INTRODUCTION

Modal analysis is a technique used in structural engineering to understand the dynamic behaviour of structures or systems. It involves the study of the natural frequencies, mode shapes, and damping properties of a structure or system under various conditions [1, 2]. In modal analysis, the words "participation" and "dominant modes" are important concepts concerning the behaviour of structures under dynamic loading situations. Participation refers to the extent to which a specific mode of vibration contributes to the overall response of a structure or system under dynamic loading, whereas dominant modes are those modes of vibration that contribute the most to the dynamic response of a structure under specific loading conditions [3].

In recent years, the development of active and passive control devices has become an interesting research area into vibration control of civil engineering structures. Passive control devices are those that are actuated by structural stimulation but do not provide feedback. They tend to be popular since they require little energy to operate and are mechanically simple and efficient. TMD is a prominent passive control device that is frequently used in buildings. The World Trade Centre Tower (1973) in New York and the John Hancock Tower (1976) in Boston were among the first practical examples of this type of control technology. Since then, a number of high-rise buildings, towers, bridges, chimneys and mast structures have been equipped with TMD to suppress wind-induced vibrations [4].

A tuned mass damper from viscoelastic material was developed and discovered that it is effective when tuned to the natural frequency over a limited band. It was also discussed that how to estimate the viscous damping of a TMD composed of viscoelastic material. For any given floor mass, damping, and stiffness, a damper can be an inexpensive and simple solution for retrofitting floors with excessive vibrations [5]. Moreover, similar studies on application of TMD in framed structures were studied [6, 7] and effective results were found if TMD with less damping ratio were used [6]. In similar research, to determine the efficiency and parameters of a passive auto-tuning mass damper (PATMD), an experimental work was conducted. The results of the 'PATMD efficiency tests' reveal its capacity to provide significant control over the structure's translational, torsional, and coupled vibrations without being tuned in any way. The tests also demonstrate that the PATMD is robust, simple, and versatile, providing it an ideal application for engineering structures [8]. It is also reported that TMD can be used to control structural vibrations [9,10].

Similarly, experimental investigation was carried out using TMD with variable stiffness. The output of the experimental test revealed that the system controls the human-induced vibrations effectively and identifies the natural frequency accurately [11]. A research based on numerical analysis and experimental investigation was made for bridge structures with TMDs and good result was found without deforming the structure [12].

To investigate the structure's behaviour with and without TMD, a one-story and two-story building frame model were created for a shake table experiment under sinusoidal excitation. The TMD was tuned to the structural frequency while maintaining the stiffness and damping ratio constant. Various parameters, including frequency ratio, mass ratio, tuning ratio, and so on, were used to assess the TMD's efficiency and robustness in terms of percentage reduction in structure amplitude. The responses were then numerically validated using the finite element approach, demonstrating that TMD may be efficiently used to control structural vibration [13].

In other experimental works, the mass damper parameters were tuned using an evolutionary operation (EVOP) algorithm. To develop a computer program, the El Centro NS earthquake data was used and it was found that a higher percentage of reduction on the roof of a ten-story structure using TMD with EVOP algorithm [14].

Similarly, group of researchers investigated vibration control for seismic structures using semi-active friction multiple tuned mass dampers (SAF-MTMD). Various friction mechanisms were used to activate all of the mass units of the SAF-MTMD during an earthquake. The study showed that SAF-MTMD effectively minimizes seismic motion, particularly at higher intensities [15]. Some experimental work was also performed using a pendulum tuned mass damper with advantages over standard TMD and discovered that the frequency may be re-tuned by adjusting the cable length [16].

Active auto-tuning compound pendulum mass dampers have generally been effective in many applications; however, they have major drawbacks: sensitivity to detuning, more prone to failure as the actuator relies on electronic components, large power consumption, installation issues, and so on [17, 18]. Moreover, third-generation active dampers have drawbacks such as design complexity, installation and operation costs, the need for continuous power supply and technical challenges for high vibration amplitudes. On the other hand, PATCPMD is simple, effective, and easily adaptable [17]. Hence, in this study, the efficiency of PATCPMD in regulating vibration and dampening responses of a steel floor system model was experimentally investigated.

2. METHODS

2.1. Materials

Mild steel was used for both the rods and the plates. The top and bottom plates weighed5.587kg and 5.692kg, respectively. The column dimensions were 9mm in diameter and each story has a height of 0.69m, with an overall structural height of 1.38m.

2.2. Equipment

2.2.1. Unidirectional shaking table

The unidirectional shaking table consisted of a 0.5m×0.5m sliding plate with a thickness of 6mm. The sliding surface had 81 holes on a 25×25mm grid and the shaking table had a maximum payload of 49.023kg. Figure 1 shows a shaking table that can operate at frequencies ranging from 0 to 6Hz, and controlled by a speed controller and a tachometer. It had the ability to produce simple harmonic motion with a maximum tilt of 20mm (± 5mm).

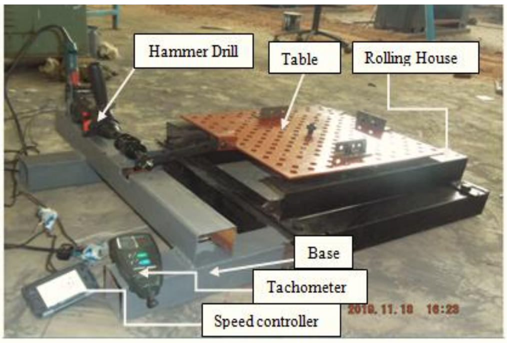
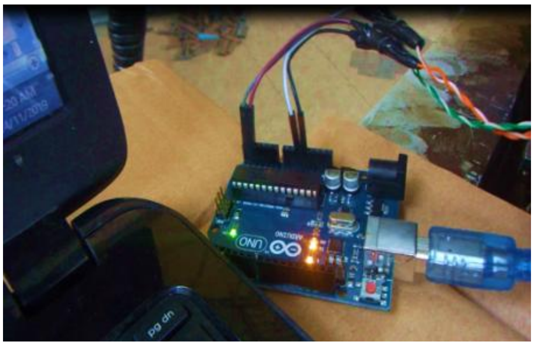


Figure 1 The shaking table

2.2.2. Gyro accelerometer and Arduino Uno board

A Gyro accelerometer shown in Figure 2(a) was attached to the frame at the location where the acceleration needs to be measured. The Gyro accelerometer was attached to an Arduino uno board (Figure 2(a)) via four data cables, which recorded acceleration and rotation data over time.



(a)

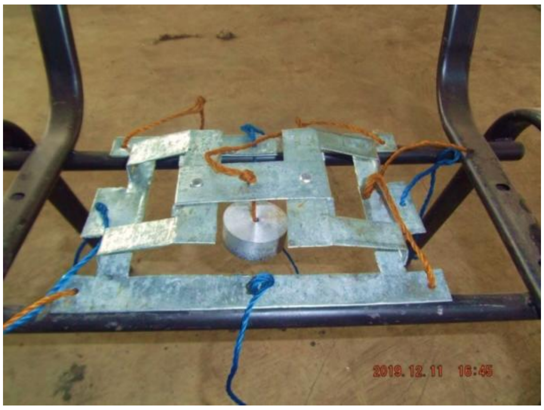
(b)

Figure 2 (a) Arduino Uno board (b) Gyro accelerometer attached to the top story.

2.2.3. PATCPMD

The PATCPMD shown in Figure 3was manufactured as a compound pendulum, although not exactly, with the link made of galvanized sheet metal weighing 0.457kg and the damper was made of aluminum weighing 0.153kg. The damper had a total mass of 0.611kg, which was approximately 4 % of the basic model's mass of 14.104kg.

The compound pendulum had a hole in the top center to suspend the mass damper, and four holes on the base to support the entire pendulum on the model's floors. The damper was suspended from the four holes at a perpendicular height of 70mm below the plates by inelastic ropes, with the damper mass suspended in the middle of the link at a height of 40mm. The steel structure model and PATCPMD suspended at the second story of the structure is shown in Figure 4.



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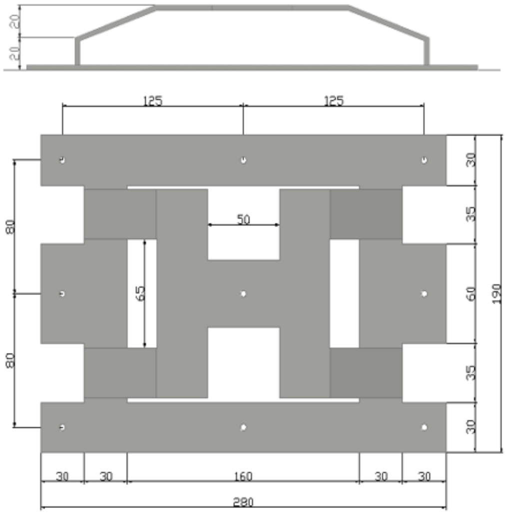
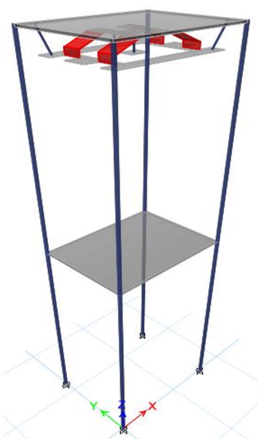


(b)

Figure 3 PATCPMD (a) photo and (b) schematic drawing



(a)

(b)

Figure4 (a) Test model (b) PATCPMD suspended at the second story

2.2.4. Measuring Tape, Wrenches, Dial Gauge and Tachometer

The tachometer shown in Figure 5was used to measure the speed of the drill which in turn controlled the oscillation of the shaking table. In addition to the tachometer, measuring tape, and dial gauge were used.

Figure 5 Tachometer

2.2.5. Speed controller

The speed controller was managed by an input voltage of 220 volts. A dimmer switch was used to controlthe speed of the hammer drill machine, while a tachometer was employed for controlling the drilling machine's rotation and also the shaking table's excitation frequency in the range 0 to 6Hz.

2.3. Experimental Setup

Figure 6 shows the experimental setup, which includes a unidirectional shaking table, gyro accelerometer and Arduino Uno board, speed controller, measuring tape, wrenches, dial gauge, tachometer, and PATCPMD. In the experimental setup, the damper is suspended at different floor levels of the steel-structured test model.

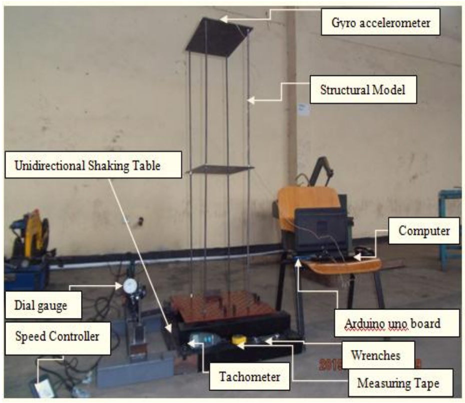


Figure 6 Experimental setup

The main structural configuration shown in Figure 6 consisted of four columns made of 1.38m high, 9mm diameter threaded steel rods, and two slabs with 300mm × 400mm × 6mm thick steel plates. The plates were fixed at heights of 0.69m and 1.38m for the first and second stories, respectively, with nuts. Each plate has four holes drilled for suspending the PATCPMD to the model. The columns were securely fastened to a unidirectional shaking table platform, ensuring that the ends were rotationally fixed.

2.3.1. Experimental Procedure

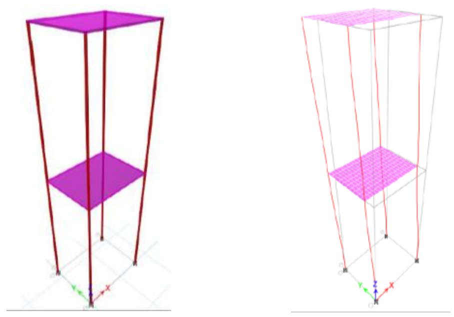
The effectiveness of PATCPMD in suppressing transitional, tensional, and coupled vibrations was examined. The free and forced vibration testing were carried out during the PATCPMD efficiency tests. Both tests were performed on the primary test model, with and without the PATCPMD. The type of tests is summarized in Table 1. The fundamental frequencies of the structure were determined via free vibration analysis. The time history of acceleration analysis plots provides information to describe the structure's dynamic behavior. Frequency analysis provides useful information regarding structural vibration. Time-history signal can be transformed to the frequency domain. The Fourier Transform (FT) is the most commonly used mathematical approach for transforming time signals into frequency domains. In structural analysis, time wave-forms are often measured and their Fourier Transforms developed. In this research, to get the time-history responses, a Fast Fourier Transform (FFT) MATLAB code was used.

Table 1 Tests undertaken for PATCPMD efficiency

No.	Type of tests	Remarks
1	Free translational vibration	The model was excited by applying an initial displacement of 10mm, measured with a dial indicator, and then releasing it.
1.1	Translational vibration in x-direction	
1.2	Translational vibration in y-direction	
2	Free torsional vibration	The model was twisted at the top story until it reached 10mm of translational displacement before being released.
3	Coupled vibration (translational and torsion)	Before being released, the model was subjected to 10mm of translational and torsional movement at the top story.
3.1	Coupled vibration in x-direction	
3.2	Coupled vibration in y-direction	
4	Forced vibration	The test model was first oriented on the shaking table to generate forced vibrations in the x-direction, and then it was turned 90° to experience forced vibrations in the y-direction.
4.1	Translational vibration in x-direction	
4.2	Translational vibration in y-direction	

2.4. Validation

Extended Three-Dimensional Analysis of Building System (ETABS) structural software was used to simulate the behavior of the primary model, which also determined its first natural frequencies and associated mode shapes. The sample model used for validation and corresponding translation in y-direction is shown in Figure 7.The dimensions of the model given in section 2.3 were entered into the ETABS software and used to validate the proposed experimental procedure and test results. The model's natural frequency for translation in both x- and y-directions and a comparison to experimental results are shown in Table 2.



a) b)

Figure 7. a) Frame model in ETABS and b) deformed shape

As shown in Table 2, the analytical results are 92 % accurate with the observed experimental values, showing that the results obtained from the experiment are found to be valid. It implies that the numerical modeling in ETABS is also considered to account for uncertainties in experimental setups [13].

Table 2 Natural frequency for free vibration

Direction	Experiment (1)	Analysis (2)	Ratio (1)/(2)
x	3.0151Hz	3.297Hz	0.916
y	3.1156Hz	3.355Hz	0.928

3. RESULTS AND DISCUSSION

This study was conducted to assess the efficiency of PATCPMD, and it presents several novel contributions that set it apart from previous research in the field. Some of these include:

i) *Innovative design concept*: the study introduces a new design concept of a PATCPMD.

ii) *Auto-tuning mechanism*: the research explores the integration of an auto-tuning mechanism within the compound pendulum mass damper.

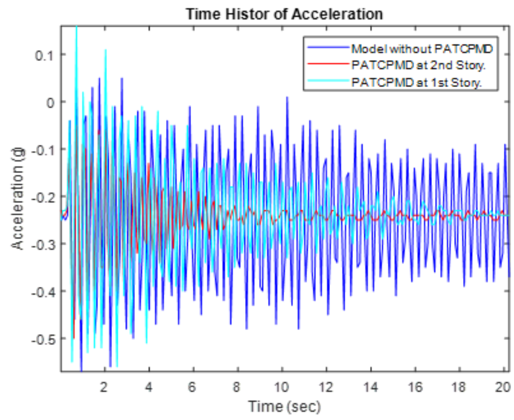
iii) *Efficiency*: an experimental work for evaluating the efficiency of the PATCPMD is done and validated.

iv) *Practicability:* the research underlines the simplicity and practical significance of the PATCPMD in mitigating structural vibrations.

Thus, in the next sub-sections the efficiency of the proposed PATCPMD system is evaluated and discussed in detail.

3.1. Free Translational Vibration

In Figures 8 and 9, the time-history graph of the acceleration response and the single-sided magnitude spectrum (SSMS) acceleration response in the x- and y-directions are shown, respectively. The results are also summarized in Table 3.



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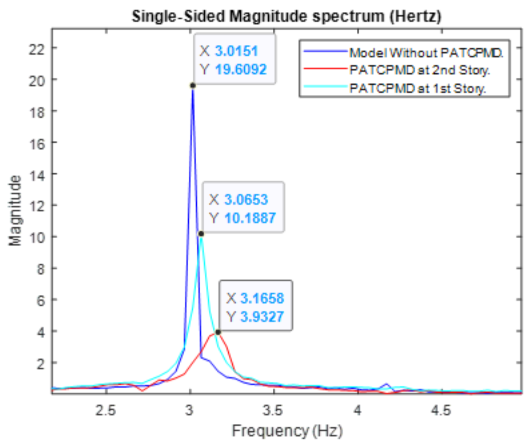

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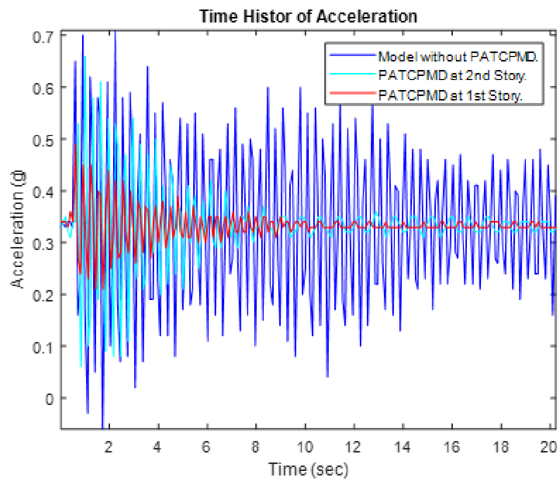
Figure 8 Free translational vibration responses in the x-direction (a) time history and (b) SSMS



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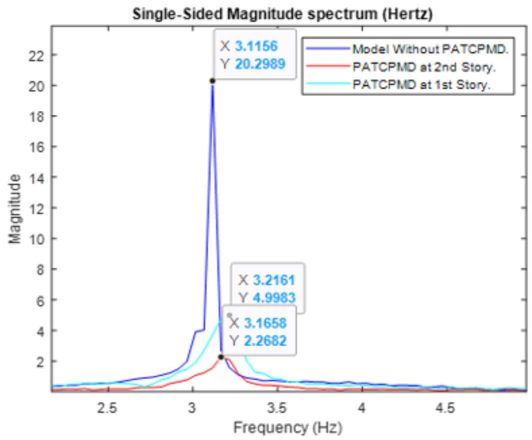


(b)

Figure 9 Free translational vibration responses in the y-direction (a) time history and (b) SSMS

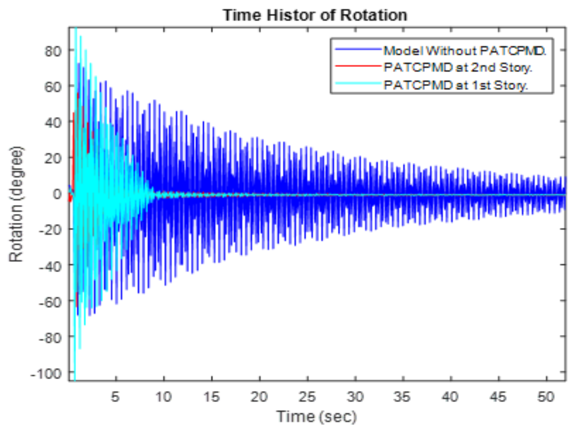
In Table 3, it is shown that the PATCPMD provides a high level of peak attenuation when hanging at the second story. The peak frequency magnitude in the x-direction, 19.609, reduced by 48 % and 80 % when the PATCPMD was placed at the first and second stories, respectively, while the peak frequency magnitude for translation in the y-direction, 20.299, is reduced by 75 % and 89 % when the PATCPMD was suspended on the first and second stories, respectively. The experimental results of this study are larger than related studies, where a 57.8 % reduction in vibration responses of the system was achieved with the application of tuned mass dampers [11].

Table 3 Free translational vibration results

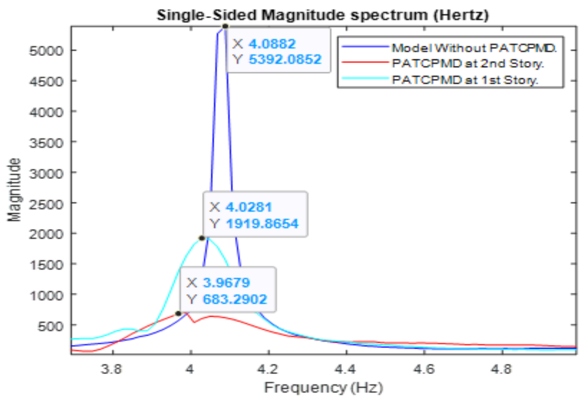
Direction	without PATCPMD	PATCPMD on 1st floor	PATCPMD on 2nd floor
Natural frequency magnitude (Hz)			
x	3.015	3.065	3.166
y	3.116	3.216	3.166
Attenuation in the translational direction			
x	19.609	10.189	3.933
y	20.299	4.998	2.268

3.2. Free Torsional Vibration

In a free torsional vibration, the system experiences torsional (twisting) motion due to the elastic properties of the materials involved [16]. The time-history and SSMS rotation responses for the free torsional vibration are shown in Figures 10(a) and (b), respectively.



(a)



(b)

Figure 10 Free torsional vibration responses (a) time history (b) SSMS

In Table 4, summary of the model's free torsional vibration results is given.

Table 4 Free torsional vibration results

without PATCPMD	PATCPMD on 1st floor	PATCPMD on 2nd floor
Natural frequency magnitude (Hz)		
4.088	4.028	3.968
Attenuation in the translational direction		
5,392.085	1,919.866	683.290

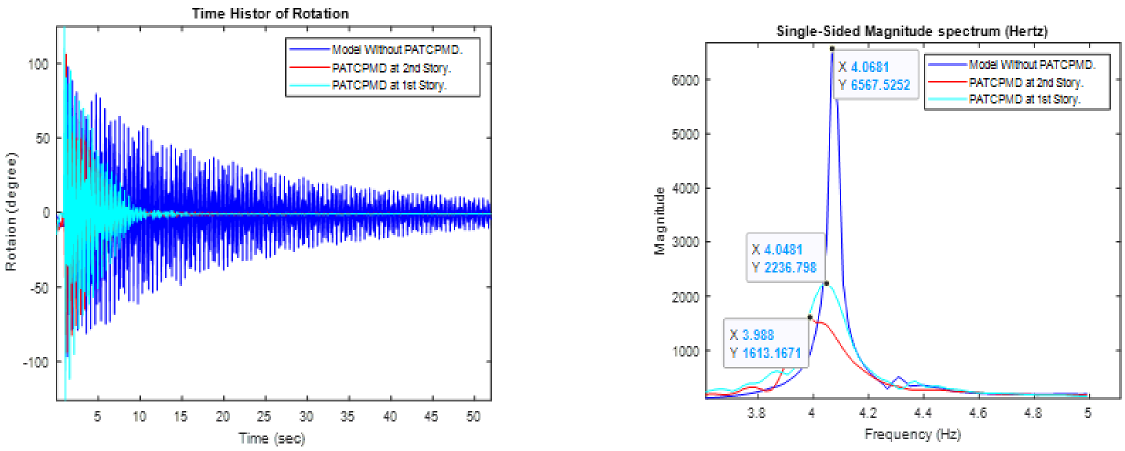
As shown in Table 4, the use of PATCPMD reduced the peak torsional frequency by 64.4 % and 87.3 % when it was suspended at the first and second floors, respectively. These values are 6.60 % and 29.5 % higher than those obtained in a previous study [11], which reported a 57.8 % reduction in vibration amplitude.

3.3. Coupled Vibration (Translation and Torsion)

Coupled vibration, involving both translation and torsion, occurs when a structure experiences simultaneous movement in both linear (translational) and rotational (torsional) directions [19].

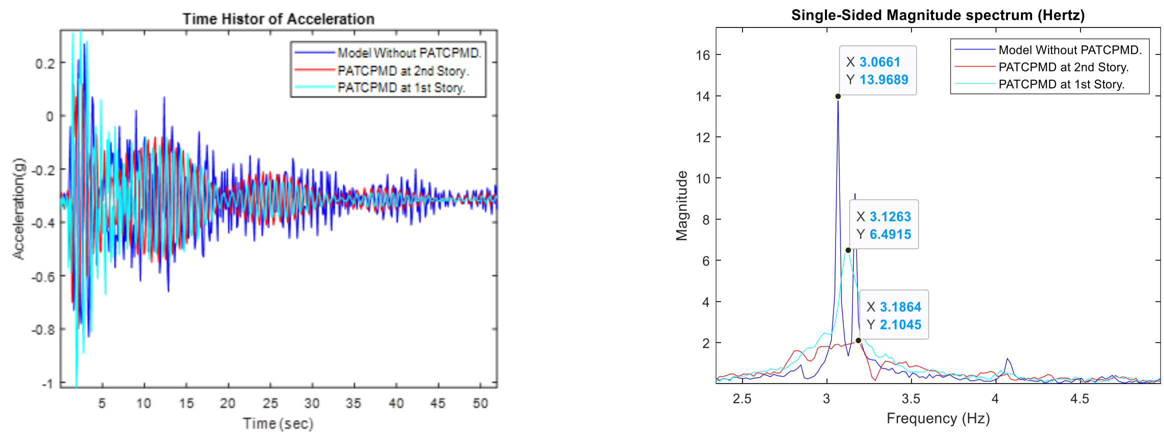
3.3.1. Coupled vibration in x-direction

In Figures 11(a) and (b), the time-history and SSMS rotation responses of the structure due to coupled vibration in x-direction are shown, respectively. Similarly, the acceleration responses are shown in Figure 12. As shown in these figures, suspending PATCPMD in the second story reduced the structure's SSMS rotation by 75 % and acceleration by 85 % when compared to the normal model. A 66 % reduction in SSMS rotation was achieved when the damper was mounted in the first story. The results are comparable with similar research suggesting that the use of TMDs is substantially more successful at reducing structural vibration by up to 77.28 % when subjected to sinusoidal ground excitations [20].



(a) (b)

Figure 11 Coupled torsional responses in x-axis (a) time-history and (b) SSMS

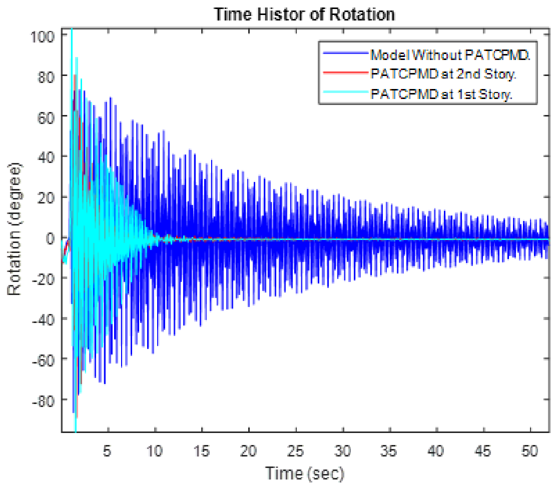


(a) (b)

Figure 12 Acceleration responses in x-direction (a) time-history and (b) SSMS

3.3.2. Coupled vibration in y-direction

Figures 13 and 14 show the time history rotation and SSMS acceleration responses for both rotation and acceleration.



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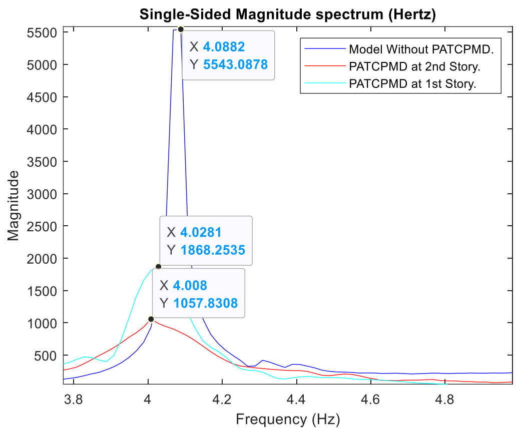
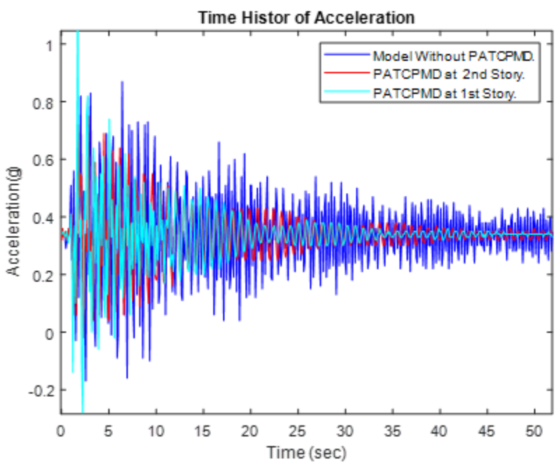


(b)

Figure 13 Coupled torsional responses in y-axis (a) time history and (b) SSMS



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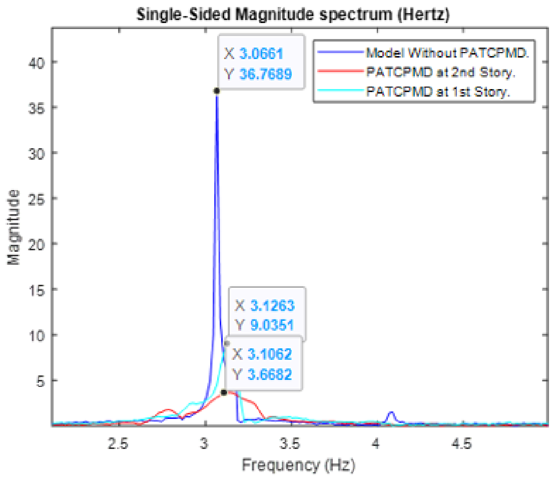


(b)

Figure 14 Acceleration responses in y-direction time-history and (b) SSMS

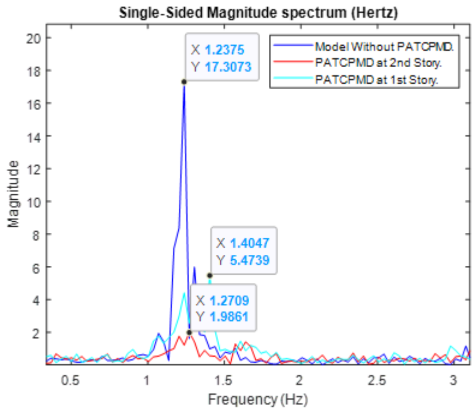
Summary of rotation and acceleration responses of the model in x- and y-directions due to coupled vibration is shown in Table 5. As indicated in the table, when the PATCPMD is suspended at the first and second stories with forced vibration in the y-direction, the peak rotation frequency magnitude reduced by 66.3 % and 80.92 %, respectively. Whereas the peak acceleration frequency magnitude reduced by 75.43 % and 90 % when the damper was suspended in the first and second stories, respectively. The results are comparable with previous studies that reported a 58 % reduction [11].

Table 5 Coupled vibration test results

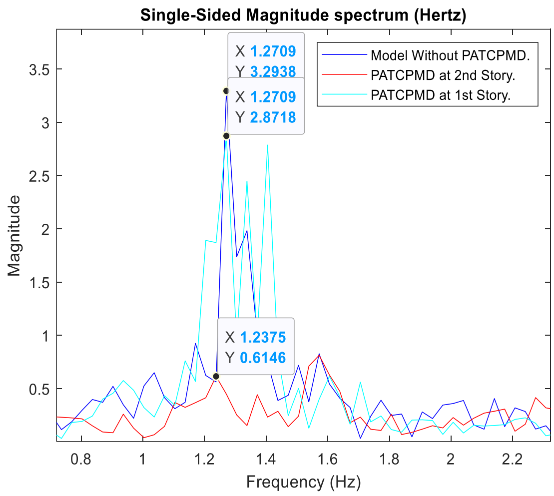
Responses	without PATCPMD	PATCPMD on 1st floor	PATCPMD on 2nd floor
x-direction			
rotation	6,567.52	2,236.79	1,613.16
acc.	13.97	6.492	2.105
y-direction			
rotation	5,543.09	1,868.25	1,057.83
acc.	36.769	9.035	3.668

3.4. Forced Vibration: Translational Vibration in x- and y-directions

The test model was initially oriented on the shaking table to generate forced vibrations in the x-direction, and then it was rotated by 90° to experience forced vibrations in the y-direction. The SSMS acceleration responses are shown in Figure 15 and the results are summarized in Table 6.



a) x- direction



b) y- direction

Figure 15 SSMS of the acceleration responses for forced translational vibration

Table 6 Forced translational vibrations in x- and y-directions

Direction of forced vibration	Natural frequency magnitude		
	without PATCPMD	PATCPMD on 1st floor	PATCPMD on 2nd floor
x	17.307	5.474	1.986
y	3.294	2.872	0.615

The results shown in Table 6indicate that the SSMS acceleration response is peak at 17.307 and 3.294 in the x and y directions, respectively. The PATCPMD's obviously controlled the forced vibration tests, where the peak vibration in the x-direction reduced by 88.5 % and 68.4 % when the PATCPMD was suspended at the second and first story, respectively. Moreover, in the y-direction, the values reduced by 81.3 % and 13 % when it was suspended at the second and first story, respectively. When the damper was suspended at the first story, the result was comparable to those published in [21], which showed that TMD reduced structural vibration by at least 13 %.

Generally, according to the experimental results of this study, in all type of tests, the frequencies ranged between 0.615 Hz and 5.474 Hz. Code recommends that structures with lowest natural frequency above 1 Hz is small and the resonant response can be ignored [22].The period of the structure for dampers with a 5 % damping ratio is between0.2T_1 and 2T_1, where T_1 is the fundamental period of the structure [23]. In this study, the fundamental frequency of the frame (*f*) was3.166 Hz (from free vibration analysis, Table 2), and accordingly, the fundamental period of the structure was found to be 0.321sec (T_1=1/3.166). As a result, the structure's period ranged from 1/5.474 to 1/0.615 (0.182 sec to 1.626 sec); in some cases, the limit is exceeded (0.2T_1 to 2T_1; 0.064 sec to 0.642 sec).

4. CONCLUSIONS

The vibration attenuation device proposed in this study, the PATCPMD, addresses the issues of excessive torsional and coupled vibrations.

The results of the experimental work indicate that the SSMS translation and rotation responses reduced by 48 % to 75 % when the PATCPMD was suspended in the first story. These reductions increased to 90 % if the damper was suspended in the second story. Furthermore, for forced vibrations, the reduction varied from 13 % to 68 % and 75 % to 80 %, when the PATCPMD was suspended at first and second stories respectively, indicating that PATCPMD was able to effectively control all types of excitations. Effective control of excitation was recorded when the PATCPMD is suspended in the second story as compared to placing it at the first story.

The effectiveness of PATCPMD in a multi-story building should be examined and further research is needed to assess the efficiency of PATCPMD under earthquake loading and frequency sweep using various parameters.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Mr. Tekleye Geda and other laboratory staff from Civil, Mechanical, and Electrical Engineering Department at Ambo University, Institute of Technology for their assistance in developing the test model for this study.

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