VIBRATION SUPPRESSION OF MULTISTOREY BUILDING USING ADAPTIVE TUNED MASS DAMPER

Muhammad Imran Mardzuki, Khairul Affendy Md. Nor*, N.H. Diyana Nordin

Department of Mechatronics,
Faculty of Engineering,
International Islamic University Malaysia

imranmardzuki881@gmail.com, affendy@iium.edu.my, nhdiyana@iium.edu.my

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*Corresponding author: affendy@iium.edu.my

ABSTRACT

An efficient engineering innovation called a vibration absorber is frequently employed to lessen vibration brought by unanticipated conditions like seismic stimulation or other external forces acting on the structure. By adjusting the absorber's mass and stiffness parameters to match the structure's natural frequency, a traditional vibration absorber can lessen the vibration of the structure. Conventional vibration absorbers, however, have a set of natural frequency that cannot be altered. To address this problem, an adaptive vibration absorber was created in this study. When a variable excitation force is applied, an adaptive vibration absorber may modify its stiffness to tune its natural frequency, enabling it to overcome the off-tuning state and resonate with the natural frequency of the main structure. This can be done by manipulating the length of spring of the absorber. The natural frequency of a three-story building construction was measured experimentally. Based on the results, a vibration absorber with a resonance frequency of 3 Hz was developed, resulting in a vibration reduction of more than 50%. To further evaluate the adaptive vibration absorber's effectiveness, it was modified to resonate at 4 Hz when installed on the three-story structure. The vibration reduction was greater than 30% at this customized resonance frequency.

Keywords: *Vibration absorber, Adaptive control, multi storey building*

1.0 INTRODUCTION

Forces applied to a structure cause vibration, which can lead to deflections and failure if the structure's natural frequency matches the excitation force in which this phenomena is called resonance [1]. Excessive vibration and resonance can result in system failures, such as the collapse of the Tacoma Narrows bridge in 1940. Vibration in high-rise buildings is a critical concern, as excessive vibrations can cause discomfort and anxiety among residents, who may feel compelled to evacuate even with minimal vibration, due to the use of lighter and thinner structural materials in seismic or wind-prone areas, posing a risk of structural damage and failure [2]. The number of natural frequencies will be equal to the number of degrees of freedom and a building's natural frequency can cause erratic floor movements and damage, especially at low-order natural frequencies where significant elastic energy is stored [3].

To control vibration, a vibration absorber is used since this strategy will improve the system's natural frequency by moving it away from the excitation frequency [4]. There are various types of absorbers used, including passive, active, hybrid, and adaptive absorbers. Passive vibration absorbers like tuned mass dampers (TMD), tuned liquid column dampers (TLCD), and liquid column vibration absorbers (LCVA) have been developed, with TMD showing superior performance [3]. TMD consists of a mass connected to the structure through a spring damper system, reducing vibration at a specific frequency [5]. However, its effectiveness decreases when the excitation frequency varies [6].

Active TMD is one of example of active vibration absorber, utilizes an active control system consisting of sensors, a controller, and an actuator to counteract the dynamic response of the structure by applying external forces, with the actuator performing control motions based on control rules to tune the excitation frequency within a broad range [5]. When the actuator is inactive, the active vibration absorber functions as a passive absorber [7]. However, active vibration absorbers can be cumbersome, heavy, and space-consuming, especially in tall structures exposed to wind loads.

Adaptive vibration absorbers utilize a reactive device that can adjust its stiffness to effectively reduce harmonic excitation [8]. The working principle is like passive absorbers but with the ability to modify the spring's stiffness to match the excitation force's frequency. By combining a tuning control system with a tunable passive device, adaptive passive control overcomes the limitations of both passive and active vibration absorbers in harmonic vibration applications.

Hybrid actuators combine great performance of passive device to control at natural frequency and active device to suppress the resulted natural frequency from passive device [9], overcoming constraints and limitations associated with single control devices [3]. Examples include hybrid vibration absorbers using tuned liquid dampers (TLD) and active mass dampers (AMD), combining the two devices for a more efficient and effective system. From this comparison, the adaptive absorber has been chosen in this research.

This research is focusing on deriving a mathematical model for a multi-story structure equipped with a vibration absorber, developing an adaptive tuned mass damper with adjustable stiffness, and experimentally verifying the performance of the adaptive tuned mass damper.

2.0 METHODOLOGY

2.1 Mathematical Modeling

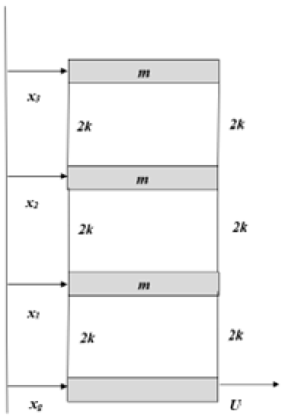

Figure 1: The schematic diagram of model building

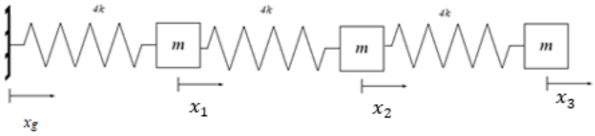

Figure 2: Equivalent spring-mass system

To derive the mathematical model for the building, the 2nd Newton's law is used [1]. The model building without a controller in Figure 1 can be simplified to spring-mass system in Figure 2. The mass for floor 1, m_1 and floor 2, m_2 are 1.4 kg while the mass for floor 3, m_3 is 0.54 kg. The stiffness for this system is the stiffness of the column where the value is 365.5 Nm^{-1}. The Equation of motion of the building is derived as in Equation (1) and can be represented as Equation (2).

$$\begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix} \begin{bmatrix} \ddot{x_1} \\ \ddot{x_2} \\ \ddot{x_3} \end{bmatrix} + \begin{bmatrix} 8k & -4k & 0 \\ -4k & 8k & -4k \\ 0 & -4k & 4k \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 4k \\ 0 \\ 0 \end{bmatrix} u \quad (1)$$

$$[M]\ddot{\vec{x}} + [K]\vec{x} = [U]\vec{u} \quad (2)$$

To find the natural frequencies and mode shape, the system is supposed to undergo free vibration where the input, U equal to 0 [1]. By using the eigenvalue and eigen vector on Equation (3), the natural frequencies and the mode shape are obtained respectively.

$$[-\omega_n^2[M] + [K]]\vec{X}_n e^{j\omega t} = 0 \quad (3)$$

For the output displacement based on the frequencies, the system can be simulated by exciting the system with input, U with sinusoidal input on Equation (4).

$$\vec{X}_n = [-\omega_n^2[M] + [K]]^{-1}[U]\vec{u} \quad (4)$$

The derivation of the mathematical model for the building with absorber follows the same procedure, but utilizes Figures 3 and 4 which include the absorber

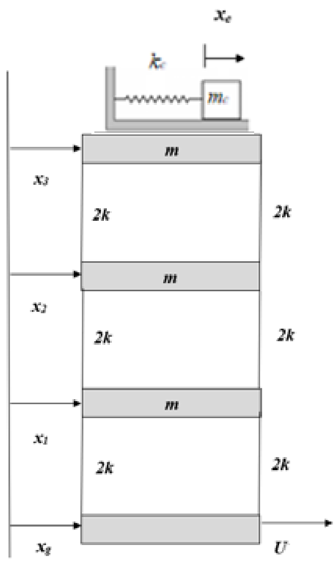

Figure 3: The schematic diagram of model building with absorber.

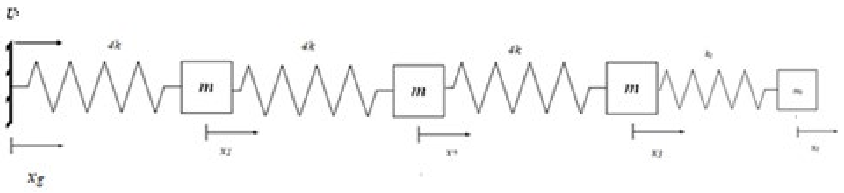

Figure 4: Equivalent spring-mass system with absorber.

The Equation of motion of the building with absorber is derived as in Equation (5).

$$\begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & m_3 & 0 \\ 0 & 0 & 0 & m_c \end{bmatrix} \begin{bmatrix} \ddot{x_1} \\ \ddot{x_2} \\ \ddot{x_3} \\ \ddot{x_c} \end{bmatrix} + \begin{bmatrix} 8k & -4k & 0 & 0 \\ -4k & 8k & -4k & 0 \\ 0 & -4k & 4k+k_c & -k_c \\ 0 & 0 & -k_c & k_c \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_c \end{bmatrix} = \begin{bmatrix} 4k \\ 0 \\ 0 \\ 0 \end{bmatrix} U \quad (5)$$

To model the adaptive tune mass damper, the spring used is from the material of carbon steel with 78GPa of modulus of rigidity, *G*, 1 mm of wire diameter, *d,* 22 mm of outer spring diameter, *D,* and 12 number of coils, *N*. The stiffness of the spring can be calculated using Equation (6) [10] and the natural frequency of the absorber can be calculated using Equation (7) [1].

$$k_s = \frac{d^4 G}{8ND^3} \quad (6)$$

$$\omega_n = \sqrt{\frac{m}{k}} \quad (7)$$

To implement the adaptive behavior for the absorber, the number of active coils is manipulated by using the stepper motor from 2 to 10. The mass used will be determined by the first natural frequency of the building and after the tuning process.

2.1 Finite Element Analysis Modeling

The simulation uses COMSOL Multiphysics software to model a three-story building using solid mechanics. The model is isotropic and has the same properties as the prototype model. Boundaries are free for base excitation analysis, and initial values for displacement and structural velocity are zero. A large mass block is added to the base to make sure the base is not tilted. The type of elements used in this modelling is tetrahedra with the number of elements of 10068. The model is drawn as Figure 5.

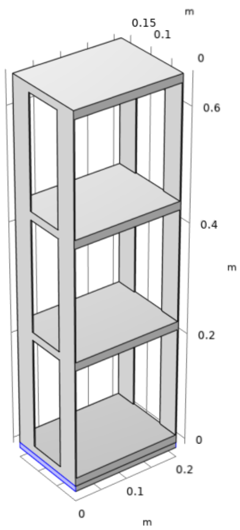

Figure 5: Three story building model in COMSOL

There are two studies done in this method. The first one is eigenfrequencies study for finding the natural frequencies in x-axis direction and the mode shape. The other one is frequency domain study for finding the displacement output at frequencies from 0 Hz to 20 Hz by applying 10 Nm^{-1} boundary loads at the base of the building.

2.3 Experimental Validation

The experiment approach is used to verify the results from both simulation methods. The model building used is as in Figure 6.

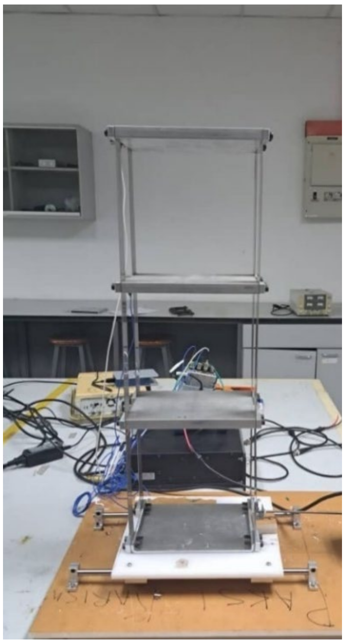

Figure 6: Three story building

The equipment used for the experiment is accelerometer, NI 9263, NI 9234, CompactDAQ, power amplifier, inertial shaker, slider, and laptop to use LABVIEW. The experiments are done without absorber, with passive absorber at natural frequency and with adaptive absorber at other frequency. The experiment setup is shown in Figure 7.

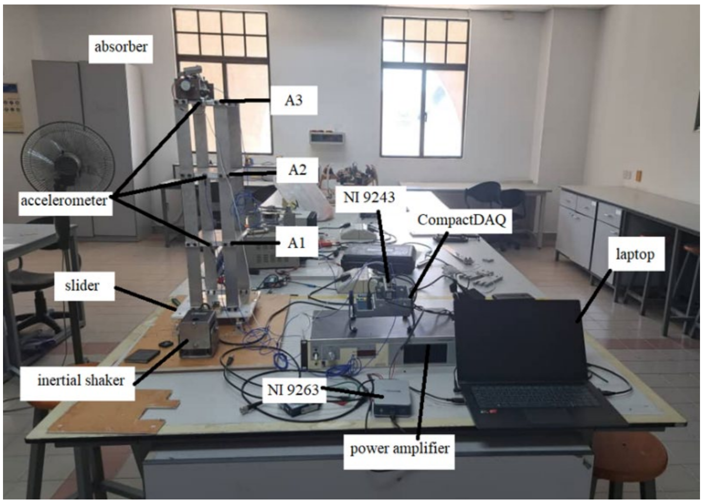

Figure 7: Experiment setup

To find the natural frequency, the system is excited by using white noise with 10^{th} order infinite impulse response filter at cut-off frequency of 60 Hz. The output acceleration of all floors will be filtered and analyzed to get the power spectrum graph. From the power spectrum graph, the dominant frequencies are obtained. Next, the sinusoidal excitation frequency will be applied around the dominant frequencies to get the power spectrum graph of the natural frequencies.

After getting the natural frequencies, the passive absorber will be tuned to match the first natural frequency. For the passive absorber, the number of coils used is two. From the Equation (7), by using the value of the stiffness and the first natural frequency, the initial mass is obtained. After that, the natural frequency absorber will be tuned to the first natural frequency of the system by changing the value of mass by using the experiment setup in Figure 8 before the experiment controlling vibration is done with the passive absorber.

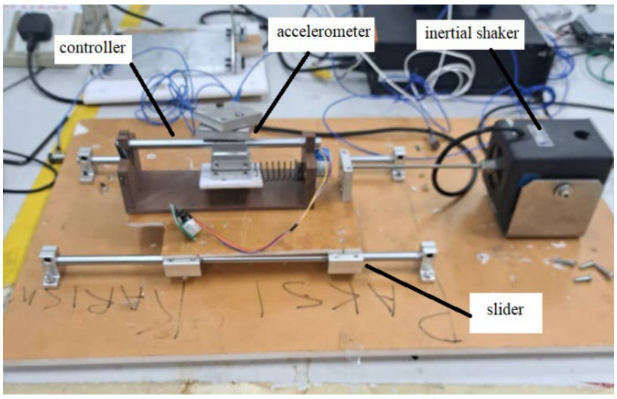

Figure 8: Experiment setup for tuning the passive absorber.

Next, the adaptive absorber will be tuned by using the same method as tuning the passive absorber. To change the number of active coils for the spring, a stepper motor is used. It is controlled by using a motor driver and Arduino. For every 360^{o} degrees counterclockwise rotation, the number of active coils is increased while clockwise rotation will make it decreases. The final design of the adaptive absorber is shown in Figure 9.

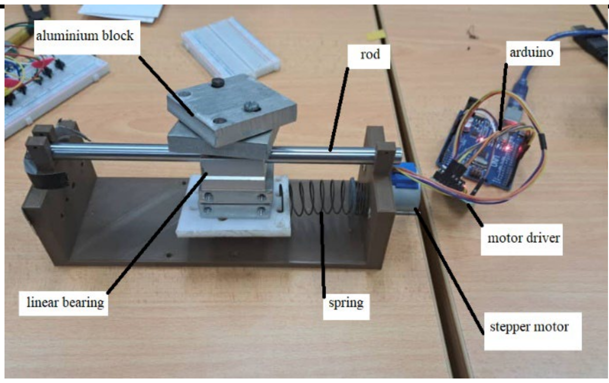

Figure 9: Adaptive tuned mass damper design

3.0 RESULTS AND DISCUSSION

3.1 Analytical Results

The natural frequencies found for the multi-storey structures are 2.7693 Hz, 7.5599 Hz and 10.4724 Hz through simulation in MATLAB. The plot of output displacement based on the frequencies for without absorber and with passive absorber are shown in Figure 10 and Figure 11.

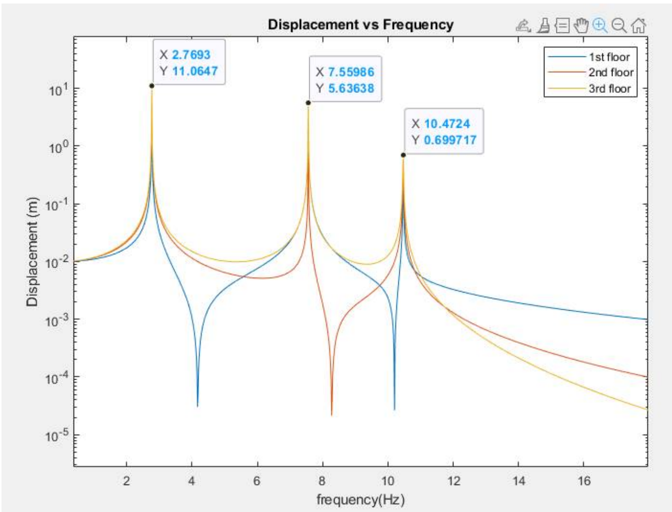

Figure 10: Plot of the displacement for each floor and the frequency without absorber.

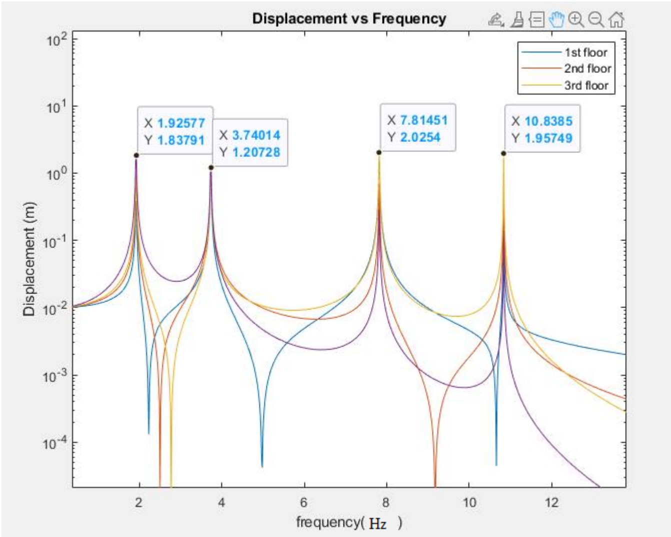

Figure 11: Plot of the displacement for each floor and the frequency with absorber.

From the plot, the first natural frequency of the system with absorber is shifted to the other two natural frequency. For the time domain graph, the comparison of the system response for all floors is shown in Figure 12, Figure 13, and Figure 14.

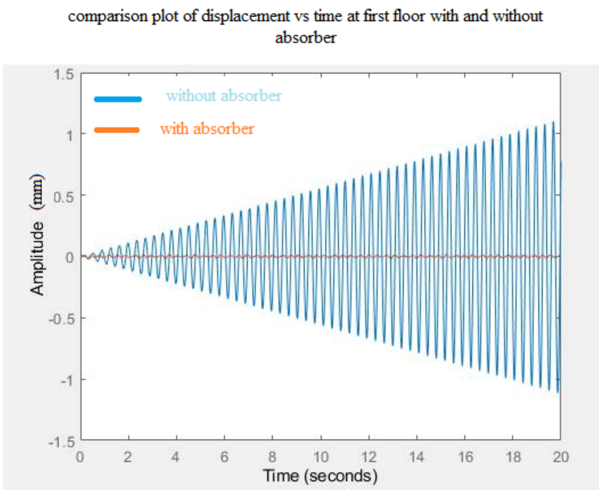

Figure 12: Comparison plot of displacement and time at first floor with and without absorber

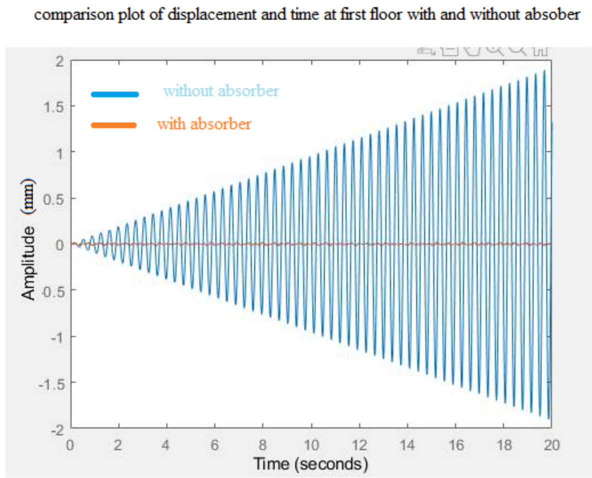

Figure 13: Comparison plot of displacement and time at second floor with and without absorber

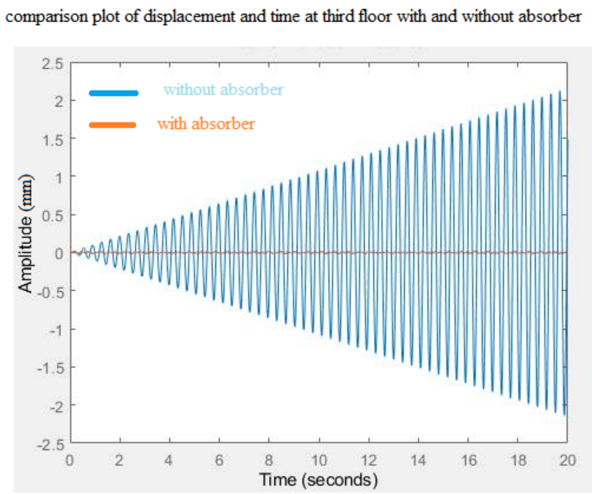

Figure 14: Comparison plot of displacement and time at third floor with and without absorber

From the graph, the amplitudes for all plot for the system with absorber are attenuated almost 100% compared to the system without absorber.

3.2 Finite element analysis results

The natural frequencies obtained for the multi-storey structures are 2.9258 Hz, 6.9042 Hz and 9.5773 Hz. For the frequency responses, the result is shown in Figure 15.

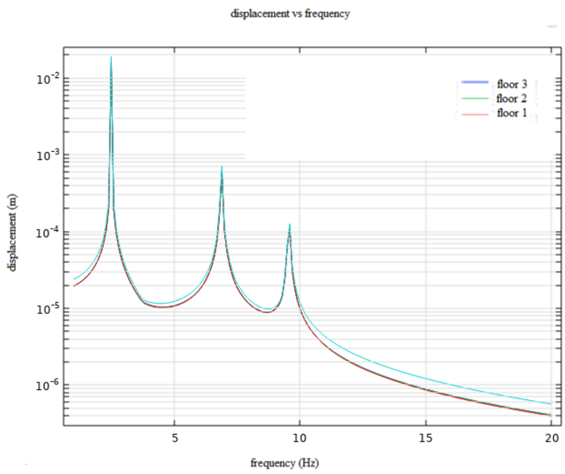

Figure 15: Frequency response of the system

3.3 Experimental results

From the excitation frequency of filtered white noise, the plot of dominant frequencies is shown in Figure 16.

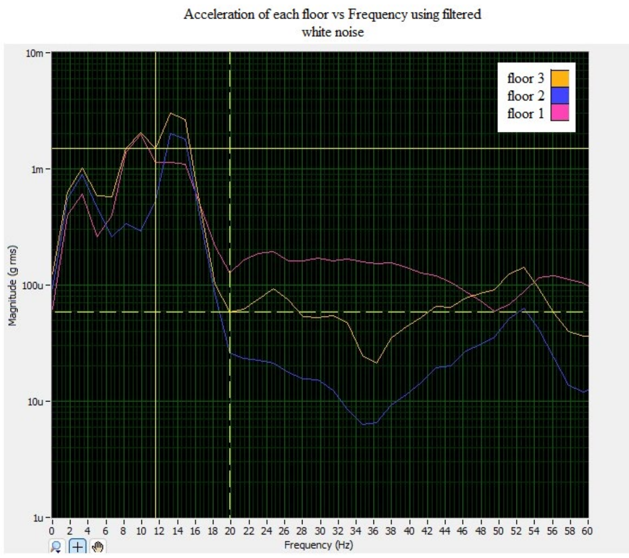

Figure 16: Power spectrum with filtered white noise excitation.

The dominant frequencies obtained from the graph are 3.5 Hz, 10 Hz and 13 Hz. The sinusoidal excitation frequencies around the dominant frequencies are used to determine the actual natural frequencies which are 3 Hz, 8 Hz and 14 Hz. The results are shown in the power spectrum graph in Figure 17, Figure 18, and Figure 19.

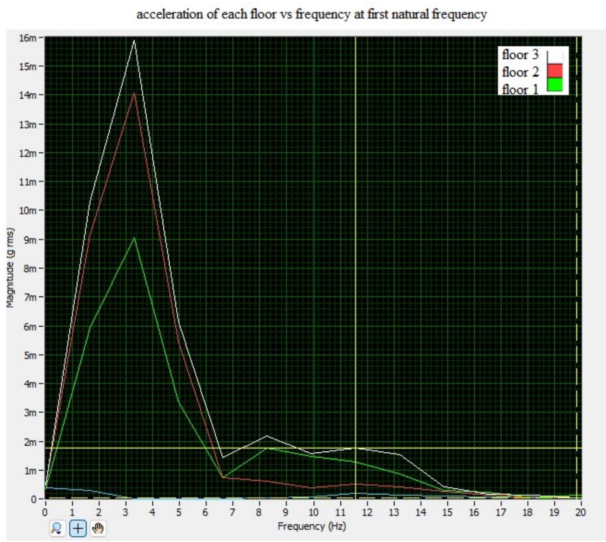

Figure 17: Power spectrum at first natural frequency

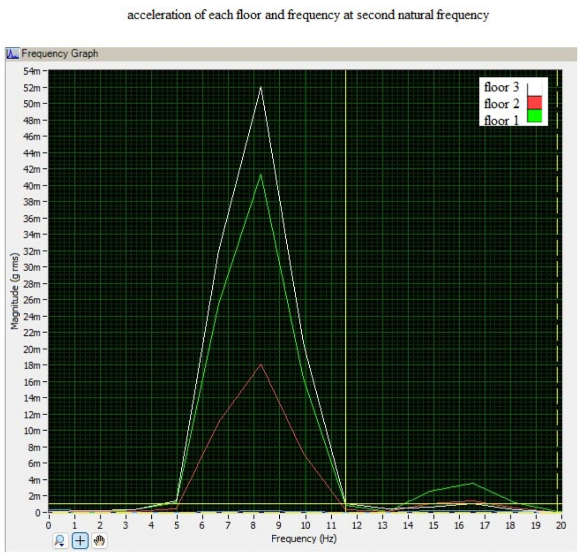

Figure 18: Power spectrum at second natural frequency

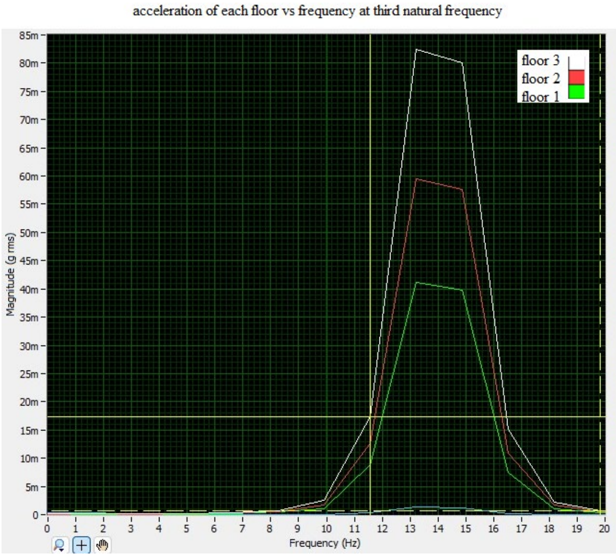

Figure 19: Power spectrum at third natural frequency

Next, for the system with passive absorber, the mass for absorber is tuned to be 0.281 kg. The result is shown for the power spectrum in Figure 20.

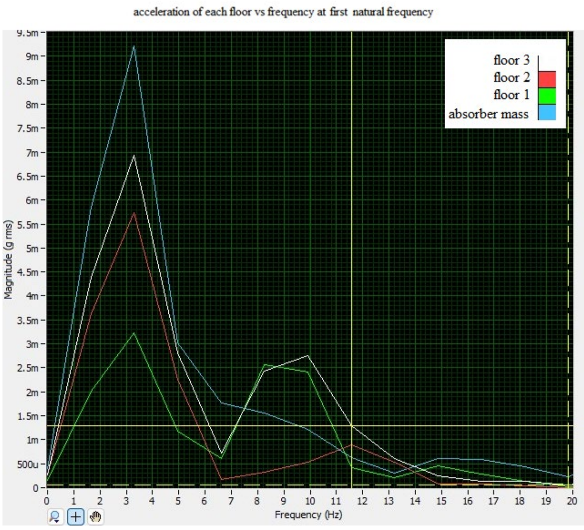

Figure 20: Power spectrum at first natural frequency with passive absorber

For the adaptive absorber, the natural frequency of the absorber based on the number of active coils is shown in Figure 21.

Number of active coils, N	2	3	4	5	6	7	8	9	10
Natural frequency, f_n(Hz)	7	5.3	4.5	4	3.7	3.4	3.3	3.1	3

Figure 21: The value for natural frequency of the absorber based on number of active coils.

For experimenting with the adaptive absorber, the excitation frequency use is 4 Hz, so the number of active coils is 5. The results for the power spectrum without and with adaptive absorber are shown in Figure 22 and Figure 23.

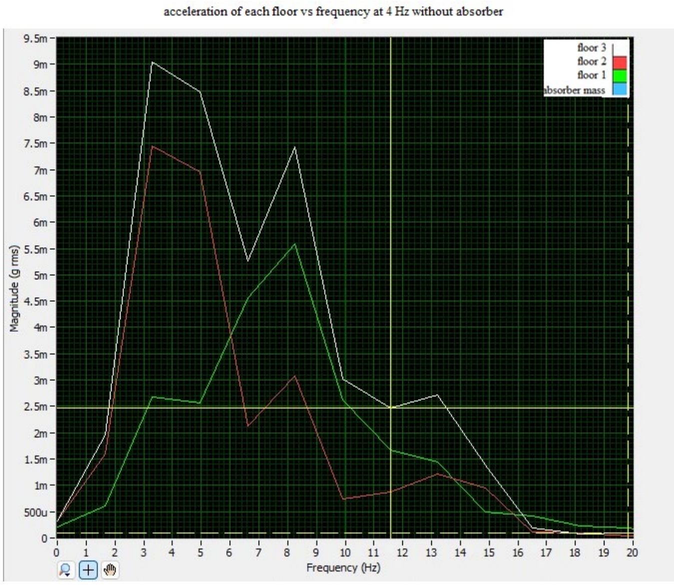

Figure 22: Power spectrum at 4Hz without adaptive absorber

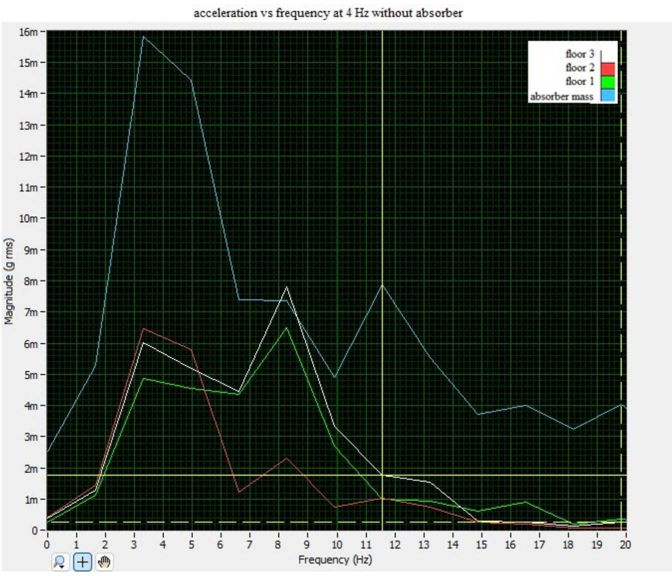

Figure 23: Power spectrum at 4Hz without adaptive absorber

3.4 Discussion

From the results of both simulations and experimental results, the natural frequencies are almost the same except for the third natural frequency where the frequency is deviated almost 4 Hz from both simulations. All mode shapes are the same for the three results. Next, for the system with passive absorber at the first natural frequencies, the result from the simulation shows that the displacement amplitude is attenuated almost 100%. However, in the experimental results the acceleration amplitude attenuated is only more than 50%. The adaptive absorber designed from this research can cover frequencies from 3 Hz to 7 Hz. Lastly, for the system with adaptive absorber at 4 Hz excitation frequency can only attenuated the acceleration signal around 30%. This may occur because the tuning process is not accurate with the factor of some noise in the system.

4.0 CONCLUSION

In conclusion, this study developed a mathematical model for a multi-story building with an adaptive vibration absorber, developed an adaptive tuned mass damper, and tested the absorber experimentally at 3 Hz and 4 Hz. A passive vibration absorber reduced resonance vibrations by over 50% at 3 Hz natural, while an adaptive absorber decreased them by over 30% when adjusted to 4.0 Hz. This was achieved by adjusting the spring stiffness by manipulating the number of active coils. Overall, this study shows that an adaptive vibration absorber can effectively reduce vibrations in three-story structure, improving structural performance and mitigating vibrations.

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