# PERFORMANCE OF LOW-COST SENSORS ON AMBIENT VIBRATION MEASUREMENT AND STRUCTURAL HEALTH MONITORING SYSTEM

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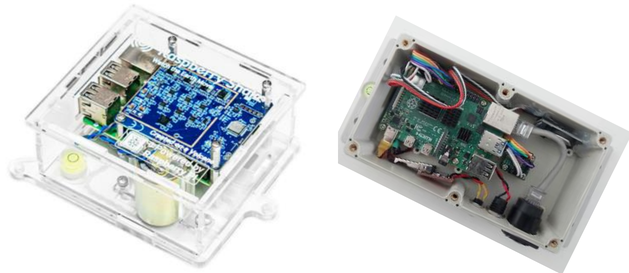
## 1. INTRODUCTION

Structural Health Monitoring (SHM) system, which involves continuously monitoring the vibration response of a building to environmental conditions during storms or seismic events, is an efficient and accurate tool for assessing the impact and structural performance. In Thailand, such systems are not widespread due to their high cost and the lack of locally developed solutions that can support the system in the long term. Nevertheless, past seismic events have made residents in northern regions, and Bangkok highly aware of the vibrations caused by these events. This awareness has raised concerns about the post-event structural integrity of buildings. It has led to business interruptions for companies and organizations occupying these buildings. Therefore, it is advisable to install SHM systems in important buildings to continuously monitor their behavior. The benefits of installing SHM systems in buildings include immediate post-event safety assessment and providing occupants with information on the building safety for future use.

## 2. LOW-COST SHM SYSTEM

The low-cost Structural Health Monitoring (SHM) system used in this research is based on Micro-Electromechanical Systems (MEMS) and a data acquisition unit. Two different models were employed: the commercially available Raspberry Shake RS4D as a complete unit, and a custom-built system using computer boards and MEMS sensors, hereafter referred to as TU-SHM. The Raspberry Shake RS4D device has been installed in a hospital building in Chiang Mai and Chiang Rai, while the TU-SHM equipment is installed in a high-rise building in Bangkok. The Raspberry Shake RS4D uses MEMs sensors capable of measuring acceleration within the range of ±2g, with a low noise level of less than 0.3 milli-g (where 'g' represents the gravitational acceleration). It continuously records data at 100 Hz and utilizes time signals from the Network Timing Protocol (NTP) system, as shown in Figure 1a. The TU-SHM system is constructed using a Raspberry Pi 4 single-board computer and an ADXL355Z MEMS Accelerometer, which is a sensor designed for measuring small accelerations at an affordable price. When assembled, the system has a data collection frequency of 100 Hz, a 20-bit AD converter, and a sensitivity of 256,000 LSB/g for the selected ±2g option, as illustrated in Figure 1b.



(a) (b)

Figure 1. (a) Raspberry Shake RS4D, (b) TU-SHM system

## 3. PERFORMANCE TESTING

The performance testing of the low-cost Structural Health Monitoring (SHM) device, which is discussed in this section, involves testing with the TU-SHM system. The main focus of this evaluation is on the performance at low-level vibrations or ambient vibrations.

3.1 Comparison with Reference Sensor

The first test is to examine the similarity of the signals obtained from the TU-SHM device and a high-quality reference sensor. Both devices were installed on the building floor, and vibration signals were measured to compare the results. In Figure 2, the red line represents the data from the TU-SHM device, while the black line represents the data from the reference sensor. The top set of graphs shows the time-domain signals, and the bottom set displays the Fourier spectra.

In Figure (a), the signal in the horizontal axis during vibrations at approximately 10 milli-g is shown. The time-domain signals in the top graph reveal that the amplitude time history of both devices is similar. When examining the Fourier spectra graph, it is evident that they correlate well in the primary frequency range of the vibration. However, there are differences in other frequency ranges, with the values from the TU-SHM device being higher than the reference sensor.

In Figures (b), (c), and (d), the measurements at very low levels for the x, y, and z axes are presented, respectively. The comparison of amplitude time history in these cases reveals that TU-SHM exhibits higher amplitude values compared to the reference sensor, which is attributed to the inherent electrical noise of the device. It is observed that the amplitude of the noise level is approximately 0.2 milli-g.

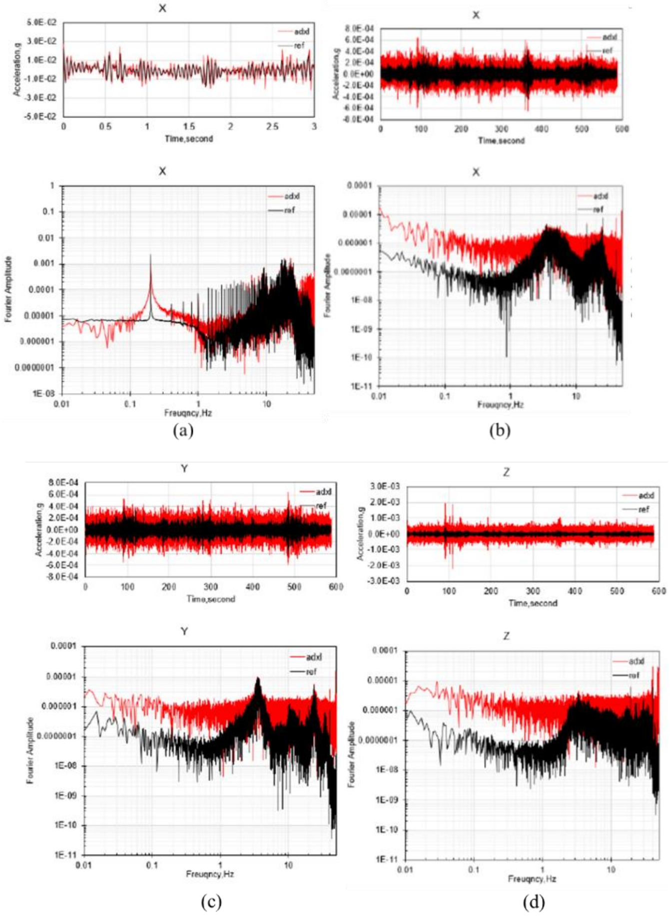



Figure 2. Examples of Time History Recording and Fourier Spectra

3.2 Coherency Tests

The next test is to examine coherency, which is an important property of devices that record data similarly for different devices, each of which may have differences arising from recording units or channels. Coherency testing involves recording data from multiple devices simultaneously and calculating the similarity of amplitudes at different frequencies. Figure 3 shows a plot between signal frequency on the horizontal axis and amplitude coherency on the vertical axis. The results shown are derived from measurements of various structures at the ambient vibration level.

The results indicate that high amplitude coherency values, close to 1.0, are found in the dominant frequency range of the signal. However, these values decrease for frequencies outside this range, and coherency values are higher for the horizontal axis compared to the vertical axis. The coherency values also vary for different levels of signal intensity. When plotting the highest amplitude coherency values against the root-mean-square (RMS) of the signals, as shown in Figure 4, it is evident that signals with amplitude coherency values exceeding 95% correspond to RMS values higher than 0.08 milli-g for the horizontal axis and higher than 0.1 milli-g for the vertical axis.

Referring back to Figure 2, it was mentioned that the noise level for time history is approximately 0.2 milli-g. However, the noise level for coherency is significantly lower. It can be concluded that the device operates effectively at signal levels higher than 0.1 milli-g for recording the main frequencies of the signals. To record amplitude, a level of 0.2 milli-g or higher is necessary.

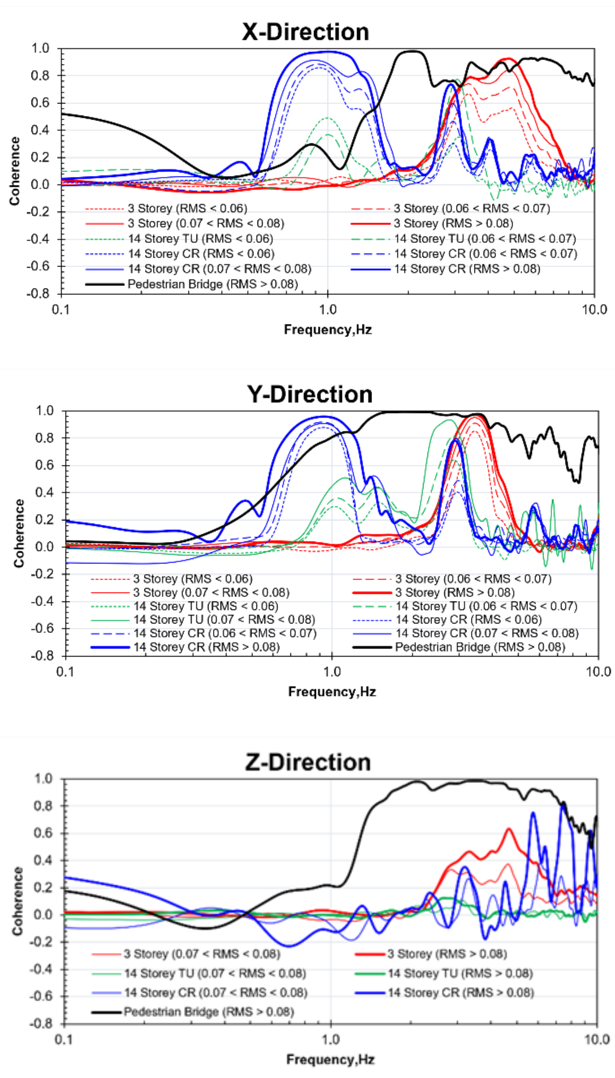



Figure 3. Amplitude Coherency plotted against Frequency

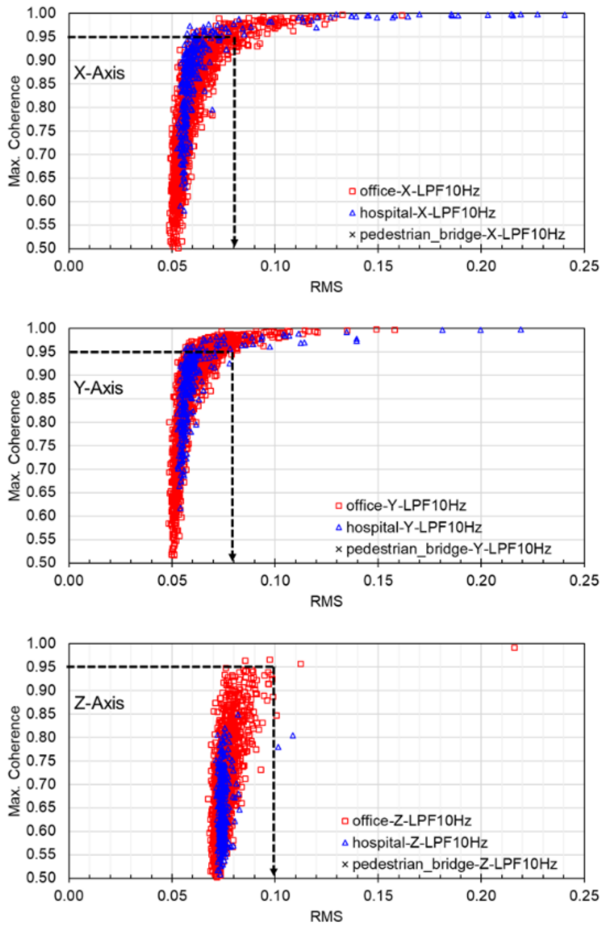



Figure 4. Comparison of Amplitude Coherency and RMS Values

## 3.3 Noise Reduction through Signal Averaging

To enhance the operational efficiency of the TU-SHM device for better performance in recording low vibrations, the next stage of research focused on evaluating the effectiveness of reducing random noise through self-cancellation from signals collected by multiple devices simultaneously. Ambient vibrations of a building were recorded using four sets of TU-SHM device. The signals in the time domain were then averaged to self-cancel random noise. A comparison was made between the signal from a single device and the average signal from 2, 3, and 4 devices. As shown in Figure 5, the Fourier Spectra of signals obtained from the TU-SHM device using signals from a single device and the averages from different numbers of devices were compared with a reference sensor. The results indicate that the Fourier magnitude of the single device had the highest values, primarily due to significant noise interference. Noise levels reduced when using the average signal from multiple devices, while the main frequencies remained accurately identifiable in all cases when compared to the reference sensor.

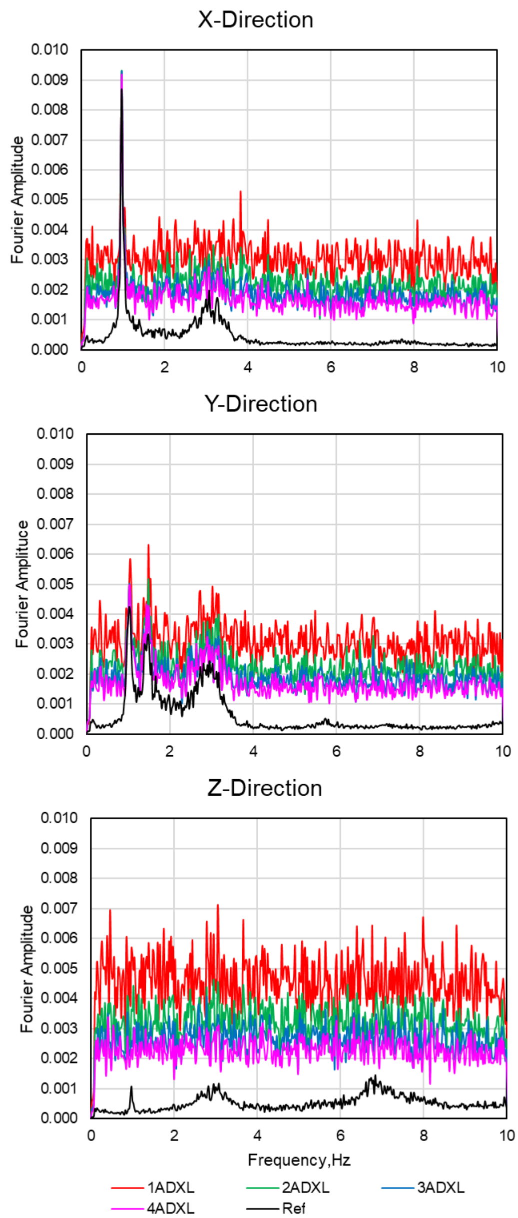



Figure 5. Fourier Spectra Comparison of Averaged TU-SHM Devices

Figure 6 illustrates the amplitude coherency results between the average signals from multiple TU-SHM devices and a reference sensor. It is evident that using a single TU-SHM device yielded lower coherency and higher RMS values or higher noise level. However, when averaging signals from multiple devices, coherency increased, indicating that the obtained signals closely matched those from the reference sensor. This also resulted in reduced RMS levels, indicating a decrease in noise due to the cancellation effect of the averaged signals.

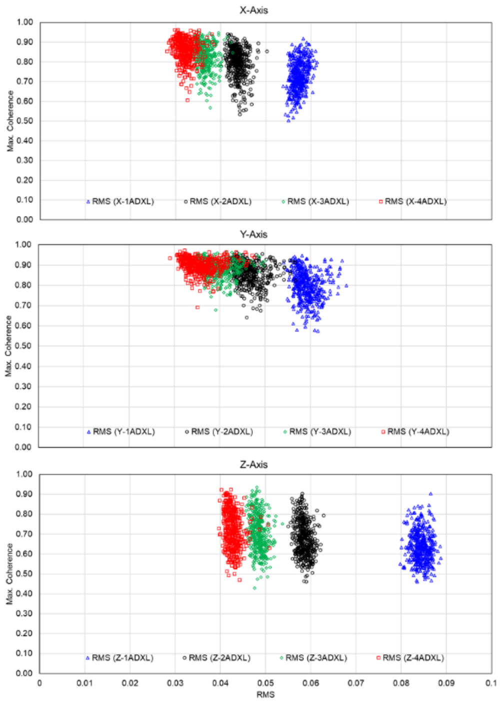



Figure 6. Amplitude Coherency Comparison between Averaged TU-SHM and Reference Sensor

## 4. PERFORMANCE OF SHM SYSTEM ON BUILDINGS

The SHM systems have been installed for long-term monitoring in hospital buildings in Chiang Rai and Chiang Mai provinces. Both buildings are 14 stories high and are equipped with Raspberry Shake RS4D devices. Additionally, the TU-SHM system has been installed in a 37-story building located in the Din Daeng district of Bangkok since March 2022. For the hospital building in Chiang Rai, a performance test was conducted to measure the building response under harmonically forced excitation. This test involved a group of 30 people swaying their bodies synchronously to match the natural frequency of the building. The test results, as shown in Figure 7, illustrate clear signals of resonance at various positions of sensors distributed within the structure.

From to the continuous monitoring over an extended period, these devices can record vibrations caused by several seismic events. The levels of vibrations were higher than the ambient condition and the occupants of the buildings could perceive these vibrations. However, there is no significant impact on the structural components of the buildings. Figure 8 shows the signals recorded from the hospital building in Chiang Mai during a 4.1 magnitude earthquake on October 20, 2022, centered in Doi Saket district, Chiang Mai. Figure 9 displays the signals recorded from the 37-story building in Bangkok during a 6.0 magnitude earthquake on June 19, 2023, with its epicenter located in the Andaman Sea, approximately 500 kilometers away from Bangkok. In both instances, the SHM systems performed well and could be used to assess the impact and performance of structures under seismic conditions. This research is currently ongoing.

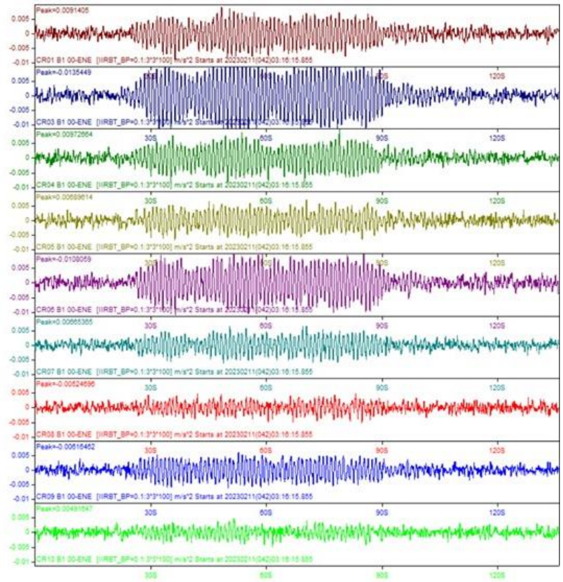


Figure 7. Forced Vibration Response Signals of Chiang Rai Hospital Building

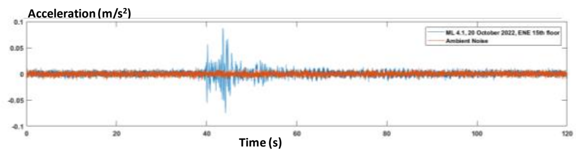



Figure 8. Recorded from the Chiang Mai Hospital Building during the 4.1 Magnitude Earthquake on October 20, 2022

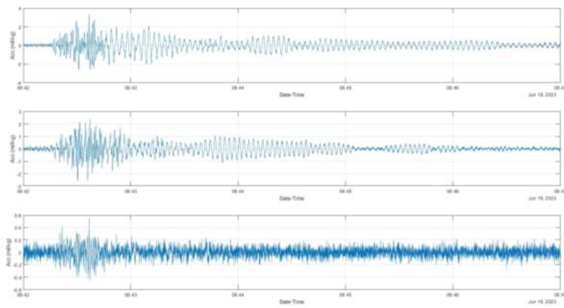


Figure 9: Seismic Signals Recorded from the 37-Story Building in Bangkok during the 6.0 Magnitude Earthquake on June 19, 2023

## 5. AUTHOR BIOGRAPHIES

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