A Structural Response Logger with Anomaly Detection using a MEMS – based System

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***Abstract* – Due to the fact that Philippines is located along the Pacific ring of fire, visual inspection to assess the integrity of a structure is commonly used in the country. Other methods also exist but require destruction of a portion of the structure or may need expensive tools. Both give reasons for the proponents to think of a solution in risk reduction among structures such as buildings. In this study, a cost-efficient system will produce a solution to the time consuming, expensive and inaccurate approximation of the integrity of a structure. Using MEMS accelerometers incorporated with microcontroller capable of sending data over the internet, a structural response logger that can detect anomaly was produced. Its accuracy was evaluated by a vibration laboratory tests while its functionality such as the alarm was tested using the Government's earthquake simulator.**

Keywords - Fire, Grounding, Earthquake, Acceleration, Intensity.

I. INTRODUCTION AND BACKGROUND

At present, there are various ways to check the structural integrity of a building. One is by non-destructive devices. Non-destructive techniques are used in the metal industry and science in order to evaluate the properties of a wide variety of materials without causing damage. These techniques require testing of material that was already fabricated. Some of the most common nondestructive techniques are electromagnetic, ultrasonic and liquid penetrant testing (Martin, Gil, & Sanchez, 2011). One of the conventional electromagnetic methods utilized for the inspection of conductive materials such as copper, aluminum or steel is eddy current non-destructive testing. These techniques cost a lot of money ranging from thousands of dollars per equipment. Furthermore, monitoring systems require more expensive apparatus like seismometer which records the movement of the ground where the building is on top. A problem arises when buildings collapse even if there is no significant motion of the building. Non-destructive techniques can do this job but with little information due to restrictions of using different apparatus.

The proposed device aims to lessen the cost of this apparatus by using MEMS accelerometers. MEMS is the acronym for micro electro mechanical system. MEMS Variable Capacitive accelerometers can measure static (constant) acceleration; the DC offset voltage will be affected by the positional alignment relative to the earth's gravity. Since these accelerometers are intended for use in critical measurement applications, the sensitivity should be verified to be certain that it is within specification. An accurate static calibration can be performed using Earth's gravity as the acceleration reference. The difference of MEMS accelerometer as compared to other accelerometers is that MEMS accelerometers are cheaper and easier to tie up with external components such as microcontrollers and other programmable devices necessary in data gathering and analysis. The proposed device in this study aims to measure the acceleration of a structure in a near real-time manner in which reading must be as accurate to those of the other structural integrity monitoring system. It also aims to determine significant changes in structural behavior before and after a significant motion of the ground occurs by comparing the acceleration data recorded before and after the significant motion through a statistical analysis tool.

Moreover, the proposed device will set its initial reading upon installation as the reference measurement when determining a significant change in the heartbeat of the structure. This means that every succeeding reading shall be compared to its reference measurement. Thus, this device can be a huge help to the society for several reasons. It can provide a more accurate analysis on a structural through a quantitative data analysis and not just by visual inspection, which is the most common methodology done by the structural engineers nowadays. Furthermore, it will allow structural engineers to assess the building integrity with a minimal effort on collecting the data using a cost-competitive device.

A. Significance

The findings and generalization of this study would be significant and beneficial to the proponents of this study, to the industry and to the society.

Industry. Results of this study will help standardize a device for structural health monitoring which provides the industry a competent means of monitoring and alerting system. It aims to give awareness for the lack of a standard structural health monitoring system. As mandated by law, building owners should have an earthquake instrumentation schemes to ensure the safety of its occupants. This offers them a cheaper but accurate device.

Society. This study would be a great contribution to the society specifically in risk reduction. Structural health analysis can alleviate the impact of disasters particularly an earthquake and incidents concerning structural collapses. The capability of the device to detect a possible structural failure through its gathered acceleration data can reduce risk and exposure to vulnerabilities and lessen the severity of losses. It can also be a big help in preparation of major seismic events that may occur.

B. Limitations

For the tareget sample, the Jhocson Residence, a 49.8 meters high condominium building, will be the target location for installation and testing. The device monitors the response of the building, specifically the acceleration, in near-real time manner. The said device can only be powered up using an AC source and a backup battery that can sustain it for few more hours. It will be using wired channels to gather reading from sensors installed all over the building towards the monitor for audio and visual alarm. The reading of the sensor is being stored to the central station day after day for one week, then overwrite it with the latest data. If there is any major tremor felt in the location, the system can provide current interpretation. Otherwise, interpretation of readings is done every 5 minutes to monitor the possibility of structural failure.

The researchers included a consultancy of a civil engineer from the faculty of Engineering Department of National University who will be responsible for the initial inspection of the structure before installation of sensors to ensure good condition of the chosen structure for monitoring. The system was for the compliance to the rules and regulation of the DPWH. The law covers private buildings that are fifty meters high, schools that have twenty classrooms or more but not less than three storeys, and commercial and industrial buildings with at least one thousand occupants. Thus, making the system a tool for risk reduction management.

For the validation of the accuracy of the acceleration reading of the proposed device in this study, one sensor node will be sent to a vibration laboratory to check its reading accuracy. Moreover, with regards to the alarm system, a hypothetical threshold corresponding to intensity 6 earthquake of acceleration from the Philippines Institute of Volcanology and Seismology (PHIVOLCS) Shaking Table which is based from the Philippine Earthquake Intensity Scale (PEIS) shall be used to ensure that the device will enable the alarm upon reaching the threshold.

II. REVIEW OF RELATED LITERATURE

In the study of Frank Neitzel1, Boris Resnik, Sven Weisbrich, and Andreas Friedrich, 3-axis accelerometer is installed in Komtur Bridge in Germany, due to its very intense and perceptible vibration. Figure below shows the inspected structure and a schematic representation of the three bridge sections with a total length of 91 m and a width of 20 m.

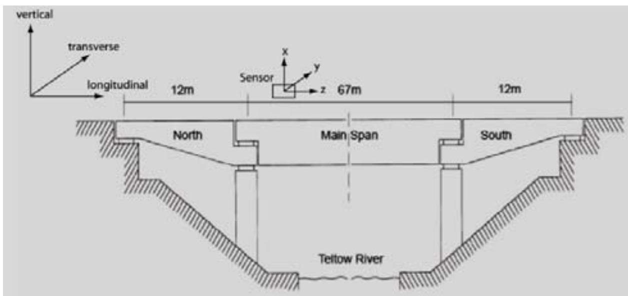

Figure 1. Picture and a schematic representation of the Komtur Bridge in Berlin, Germany

A reference measurement is required where the accelerometers record vibrations within the same area. This guarantees the comparability of the signals of the sensors. Based on this data, a correction function can be applied that represents a relative calibration. Sensors are placed on determined position on the bridge. Sufficient measurement is produced for subsequent analysis. The vibrational measurements are most relevant in vertical directions while there are no significant natural frequencies obtained in longitudinal direction.

The noise of the measurement along z-axis is about ten times higher than noise along xy plane. Therefore, the x and y axes have to be in transversal and vertical direction of the bridge. The z-axis has to be aligned parallel to the longitudinal direction of the bridge.

High-pass filter is used to rectify, with corresponding, predetermined correction function and subsequently reduced of an offset and drift, the recorded time series of each sensor. Ambient windows are the sections of ambient vibrations. It used to determine the natural frequencies.

III. RESULT AND DISCUSSION

A. Calibration of Accelerometer

The main objective of this activity is to ensure that the acceleration reading of every sensor will be identical if they are receiving the same amount of trigger input. Since, there is no available shaker that can be used to trigger the accelerometers at a specific amount of vibration, the proponents decided to utilize the presence of gravitational acceleration. It is expected that every accelerometer must be sensing an acceleration of 1g or 9.8 m/s2 if its axis is parallel to the direction of gravity. Most of the time, the reason for unequal reading of accelerometers given the same input is due to rescaled measurement of the reading of an accelerometer (whether scaled larger or smaller) or maybe due to the misalignment of its axis upon fabrication. To correct such error, the proponents gather the reading of the accelerometer projecting every axis to be of the same direction as the gravitational acceleration such as shown in figure 2.

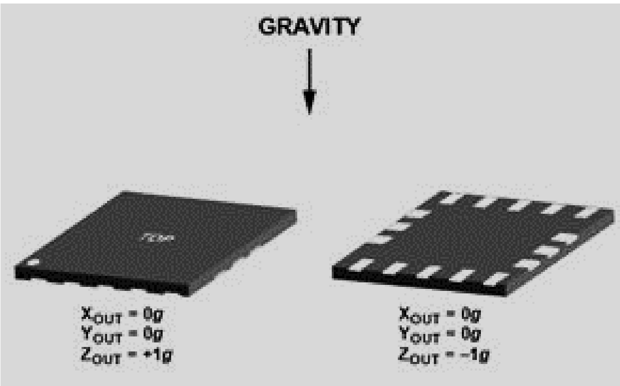

Figure 2. Orientation of Accelerometer in two reading

Ideally, the reading must be +256 bits and – 256 bits for upside down axis. However, shifting of reading and rescaling will cause a different result. Just like what is shown in figure 3, the proponents determined the amount of shift of the reading of the accelerometers (whether shifted down or up) to centralize its measurement then rescale it to obtain a range of 512 bits.

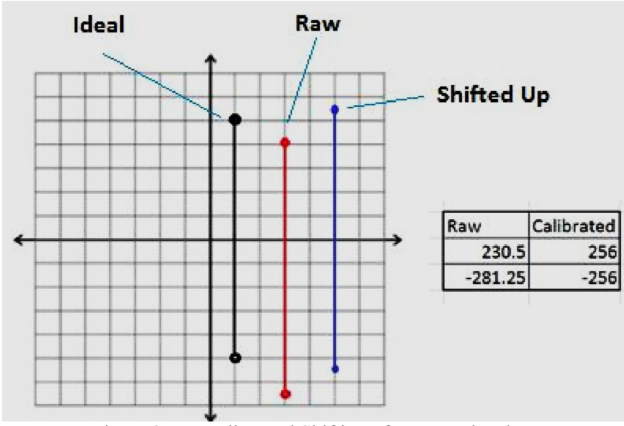

Figure 3. Rescaling and Shifting of Measured Values

Then to correct the misalignment, the concept of the rotation of axes will be used to force the gravitational acceleration be read by the vertical axis solely. Shown in figure 4 is the derived formula for the value of pitch and roll.

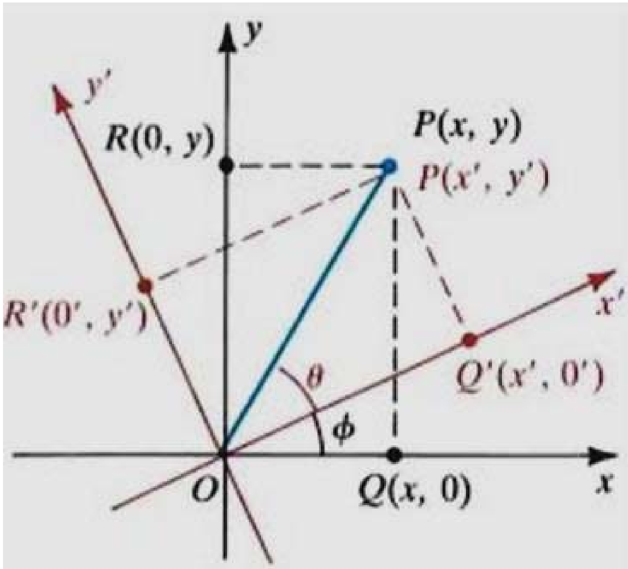

Figure 4. Rotation of axes in 2D

For x @ ± 1g

If z/y = + then:

$$\theta = tan^{-1}\left|\frac{z}{y}\right|$$

If z/y = - then:

$$\theta = 2\pi - tan^{-1}\left|\frac{z}{y}\right|$$

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If x/y = + then:

$$\phi = \frac{3\pi}{2} + \sin^{-1}\left|\frac{x}{r}\right|$$

If x/y = - then:

$$\phi = \frac{\pi}{2} - \sin^{-1}\left|\frac{x}{r}\right|$$

$$x' = -(y\cos\theta + z\sin\theta)\sin\phi + x\cos\phi$$
$$y' = (y\cos\theta + z\sin\theta)\cos\phi + x\sin\phi$$
$$z' = -y\sin\theta + z\cos\theta$$

Shown in the table below is the comparison between the raw and calibrated reading of the accelerometer with the z-axis perpendicular to the ground. As can be seen, the horizontal axis detects no acceleration while the z axis receives all the acceleration, which is expected given the said orientation of the accelerometer.

TABLE I. ROTATED AND UNROTATED MEASURED VALUE

	Unrotated			**Rotated**	
x	y	z	x	y	z
19	19	242	1	0	255
19	18	241	0	0	256
18	18	240	0	0	255
19	17	241	0	-1	255
19	19	242	1	0	255
18	17	242	-1	0	256
19	18	241	0	0	255
19	18	243	0	0	255
18	18	242	-1	0	255
19	18	241	0	0	256

B. Installation of the System in the Chosen Building

The floor plan of the building was given to the involved Licensed Civil Engineer for evaluation and identification of the center of rigidity. The center of the rigidity is the spot of the building that best reflect the heartbeat of the building. Upon determination of the center of rigidity of the building, the Licensed Civil Engineer checked the whole structure visually and will then gave the approval for installation. Since the chosen building is lesser than 50 meters high, it is not required to used up 3 accelerographs. Therefore, the proponents installed 2 accelerographs in the building, one in the base (for ground motion detection) and one at the roof deck (for the building movement and displacement detection). Shown in figure 5 is the floor plan of the roof deck and the identified location of the center for rigidity.

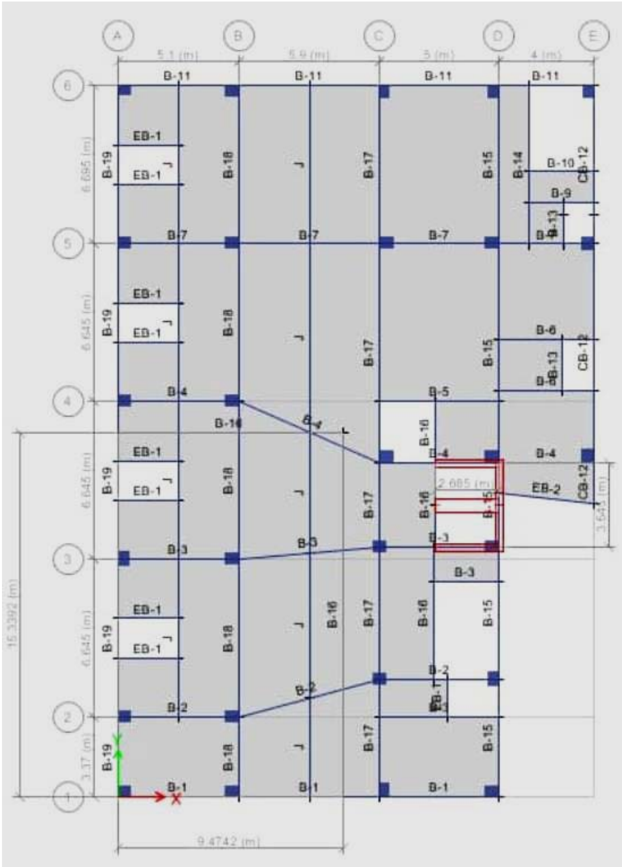

Figure 5. Floor Plan of Roof Deck

The installed accelerographs utilized the AC supply of the building and used USB cables to interface every accelerographs to the central monitor, which was located at the lobby.

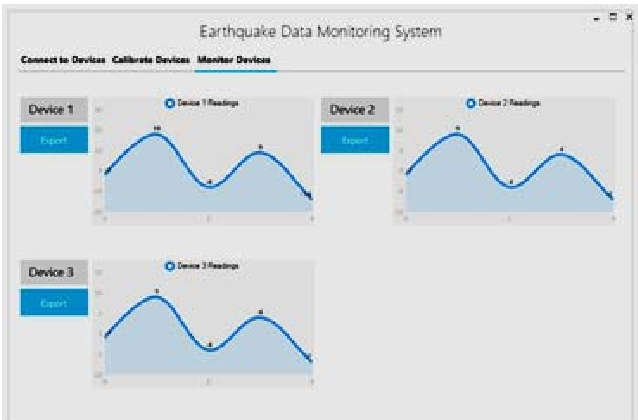

Figure 6. Graphic User Interface (GUI) displaying waveform of the sensor nodes

The GUI displayed in figure 6 shows the moving waveform of the data coming from each sensor nodes which can be easily interpreted by any viewers. If in any instance,

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an event occurs, the waveform is expected to surge vertically.

Thus, indicating an even which can be the occurrence of an earthquake. Since storage is limited, the day to day data were exported for paper-based storage of data.

C. Device Testing and Evaluation

The accuracy of the measurement of the sensor node proposed in this study was verified by a vibration laboratory that has complete equipment capable of triggering the sensor node at different level and frequency. Upon completing this test, a test report validated the specification of the developed sensor node of the proponents in this study and are as follows.

TABLE II. SENSOR SPECIFICATION

Specification	Corresponding component/action to be used
Accuracy	Less than 0.3% anomaly (0-30Hz)
Store seismic activity information as gathered by the attached accelerometer	YES, with 64GB daily allowance for data storage
Provides real-time alarm information during an earthquake event	YES, via computer monitor and buzzer
Equipped with internal back-up battery	YES, 20,000 mAh power bank
Minimum of three components	YES, ADXL3452 Triaxis MEMS Accelerometer
Sensitivity: 2g	YES, ADXL345: 2g to 16g
Environment: IP67	YES, suppliers warranty
Sampling rate: minimum of 100 sps	EXCEEDED

Moreover, with regards to the proper enabling of the alarm notification, the proponents used the MMDA Earthquake simulator as its vibration inducer. First, measurement of acceleration at intensity 6 was recorded and was set as the reference threshold in detecting a critical earthquake. The idea of using intensity 6 as the reference for critical earthquake intensity is based on the categorization of PHIVOLCS of intensity levels and its corresponding hazard, summarized in the table below is the PEIS categorization for intensity 6.

TABLE III. PHILIPPINE EARTHQUAKE INTENSITY SCALE (PEIS)

Intensity Level	Description
VI Very Strong	• Furniture and other heavy objects are displaced • People may lose balance. • Small church bells may ring. • If on the road, it may feel like driving with flat tires. • Very old or poorly built houses and man-made structures are slightly damaged though well-built structures are not affected. • Limited rockfalls and rolling boulders occur in hilly to mountainous areas and escarpments. • Trees shake.

Then, upon putting this threshold in the codes of the device, the enabling of alarm was tested if working properly and summarized below is the result of the trials conducted.

TABLE IV. DEVICE ALARM RESPONSE TO INPUT

Intensity Level	Response of the device	Remarks
Below 6	Alarm OFF	Correct
At 6	Alarm ENABLED	Correct
Above 6	Alarm ENABLED	Correct

IV. CONCLUSION

The main goal of this study is to provide a device that will monitor the response of a structure in a near real time as an easier way of determining the integrity of a structure with or without an event and will lessen the need for the personal visitation of a structural engineer for integrity inspection visually. As part of achieving this, a statistical tool was used to evaluate whether the read response of the structure is already significantly different from its natural response. Upon the execution of this, the following are concluded.

First is that it is necessary to create a mechanism that will forced accelerometers to obtain equal response at the same trigger level since it is already evident that every accelerometer, specially MEMS, have a built-in inaccuracy due to some reasons such as rescaled output, misorientation, etc.

Second, it is evident that the most significant axis for the accelerograph is the vertical axis and must be highly accurate since most of the significant vibrations are happening along the vertical axis. Thus, it is required for a structural response logger to have three components of axis.

Moreover, with respect to the proper functionality of the device, , it can be concluded that the proposed device in this study create a significant impact in the risk reduction of possible danger that faulty structure and earthquake may cause to many people's lives. The way it gives near-real monitoring and a time to time detection of anomaly is an efficient way of giving information to those who are in the structure with regards to their safety it's novelty to other existing accelerograph, that reads structures acceleration only, is its ability to interpret what it read and create a conclusion out of it.

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