Building Health Monitoring through Vibration and Inclination Measurements Using Two Techniques

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***Abstract*—Accumulation of vibration and inclination data is important for health monitoring of building. If the condition of buildings can be monitored regularly and abnormalities is detected, damage of the building can be found. In this paper, two types of measurement devices were evaluated and compared to measure the condition of buildings. One is an inclination angle measurement device using a bubble tube and a camera. The other is a vibration and inclination measurement device using a MEMS type accelerometer sensor. Both methods can measure slight inclination angles of a building. The accelerometer can also measure vibration waveforms due to earthquakes and time variation of building vibration. The vibration and inclination angle of a mid-rise building were measured. Daily variations of the angle due to sunlight on the building, vibrations caused by human activity, and seismic waveforms were measured. It was found that the method using a bubble tube can measure angles with less noise than the method using an accelerometer. The two methods employed in this paper are found to be effective as a means of knowing various building characteristics.**

***Keywords*—health monitoring, building, sensor network, inclination angle, vibration, earthquake**

I. Introduction

Vibration and inclination angle measurements are important for predicting natural disasters such as landslides. They are also important for diagnosing the health of structures of buildings. In the case of landslides, the detection of small angular changes in the ground just before an actual landslide can alert people.

Buildings are subject to various influences such as sunlight, wind, rain, earthquakes, human movement and elevator movement. If the characteristics of a building are known through continuous measurement, it will be possible to detect structural damages caused by large earthquakes using anomaly detection methods.

Until now, various methods have been proposed to measure the condition of buildings for structural health monitoring [1–7]. Various methods for disaster prevention have been proposed [8–12].

We have developed a technique to measure inclination angle using bubble tube and camera [13, 14]. It is a low-cost and precise measurement method with an accuracy of about 0.0001 degrees. The highly sensitive bubble tube is a curved cylinder and can measure inclination in one direction. Continuous measurement of the inclination angle of a building was performed. The results showed that the inclination angle varied with a daily cycle, and that the cycle was more pronounced in clear weather. This is explained by the thermal expansion of the building. The relationship between the daily variation of the inclination angle and solar radiation was evaluated using a machine learning classification algorithm [15].

On the other hand, MEMS type sensors are widely used for vibration and inclination angle measurements. Although MEMS sensors have the advantage of being compact and easy to measure, they have some problems such as high temperature dependence.

In this study, angle measurement using a bubble tube and vibration and inclination angle measurement using a MEMS sensor were simultaneously performed and compared.

II. Inclination Angle Measurement Using a Bubble Tube

Fig. 1 shows the concept of inclination angle measurement using a bubble tube. The inclination angle of the device is determined by taking a photograph of the bubble tube and determining the position of the bubble. If the amount of movement of a bubble is Δx, the angle is θ, and the radius of curvature of the bubble is R, the relationship between the amount of movement and the angle is given by the following equation when the angle is small.

$$\Delta x = R\,sin\theta \approx R\,\theta \tag{1}$$

If the radius of curvature of the bubble tube is large, a slight change in angle causes the bubbles to move. In general, inclination angle sensors are often affected by temperature changes and electrical noise. In contrast, in this method, the size of the bubble changes with temperature change, but the center position of the bubble does not change. Therefore, this method is not easily affected by temperature changes. In addition, since the

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measurement is made by camera photography, electrical noise is not generated. These are the main features of this method.

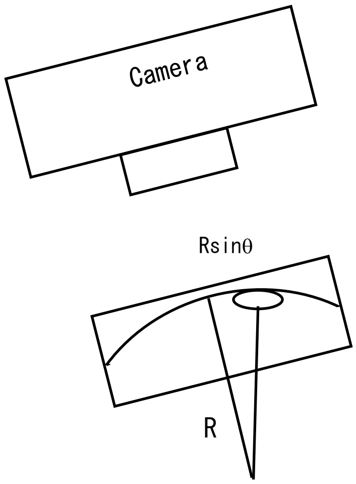


Fig. 1. Concept of inclination angle measurement using a bubble tube.

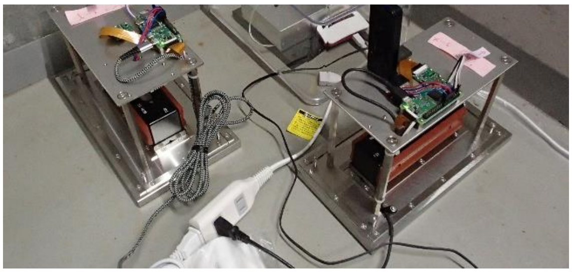


Fig. 2. Photograph of the inclination angle measurement system.

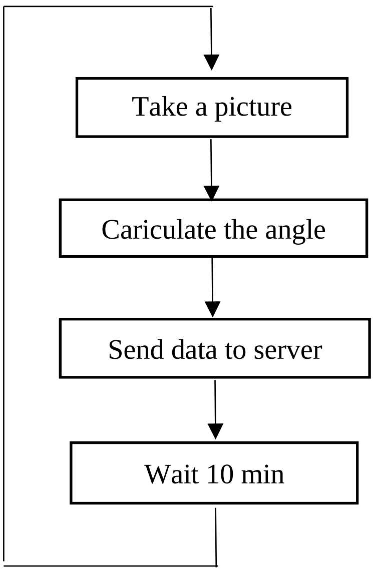


Fig. 3. Flowchart of the inclination angle measurement.

A bubble tube with a radius of curvature of 50 m was used for the measurement. The distance between the bubble tube and the camera is 15 cm. Photograph is taken once every 10 minutes. The left and right end positions of the bubble are calculated by template matching. From these positions, the center position of the bubble is determined and converted to angle data. This method does not measure the absolute value of the angle, but only measures the relative change of the angle. The reason for this is that absolute angle measurements require strict calibration. When determining the daily variation of building angles, it is not necessary to measure absolute values of angles.

Fig. 2 shows a photograph of the measurement device. Fig. 3 shows a flowchart of the inclination angle measurement. The angle measurements were taken using a Raspberry Pi and Picamera. Since a single bubble tube can measure angles in one direction, two devices were set up orthogonally to measure angles in X and Y directions.

III. Vibration and Inclination Angle Measurements Using Accelerometers

With advances in MEMS technology, inexpensive, high-sensitivity accelerometers are available. For example, the ADXL355 from Analog Devices has a sensitivity of 256,000 LSB/g and a noise density of 25 $\mu g/\sqrt{Hz}$ at a cost of about \$50. Table I shows the specification of ADXL355.

TABLE I. Specoification of Accelerometer (ADXL355)

Voltage Range	2.25 V to 3.6 V
Sensitivity	256,000 LSB/g
Noise Density	25 $\mu g/\sqrt{Hz}$
0 g offset	0.15 mg/°C
Digital serial peripheral interface	SPI or I2C
Output Full-Scale Range	±2.048 g

The Raspberry Pi and ADXL355 are connected via I2C. The accelerations in X, Y and Z directions include gravity acceleration and vibration. The variance of the data is the vibration component, and the mean of the data is the angle component. If the axial components of the gravitational acceleration are g_x, g_y, g_z and the gravitational acceleration is g_0, the inclination angle is given by the following equation.

$$(\theta_x, \theta_y, \theta_z) = (\sin^{-1}\frac{g_x}{g_0}, \sin^{-1}\frac{g_y}{g_0}, \sin^{-1}\frac{g_z}{g_0}) \tag{2}$$

Fig. 4 shows a photograph of the vibration and inclination angle measurement system. The device was placed directly on a concrete substrate near the center of the seventh floor of an eight-story building. Fig. 5 shows a flow chart of the vibration and inclination angle measurement system.

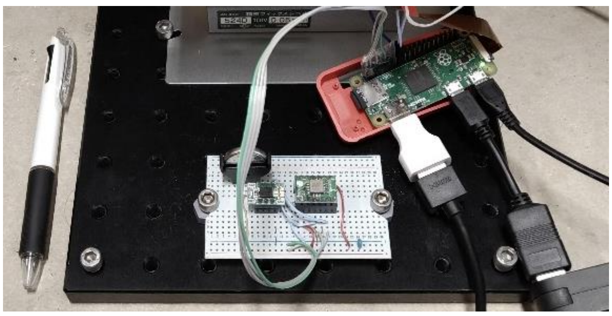


Fig. 4. Photograph of the vibration and inclination angle measurement system.

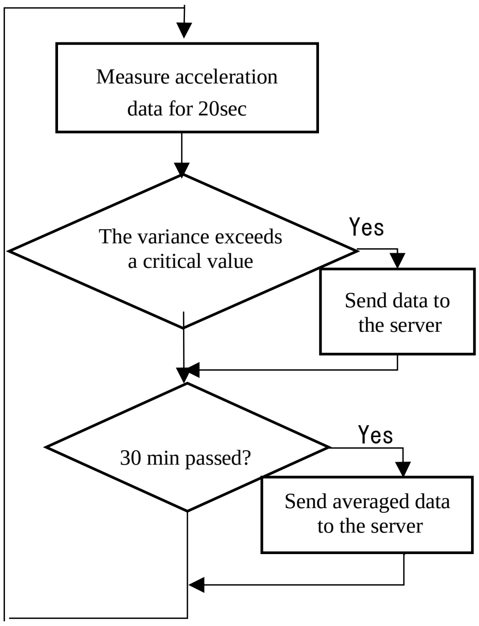


Fig. 5. Flowchart of vibration and inclination angle measurement.

A single vibration measurement is made with a sampling rate of 100 Hz, and 2000 data are acquired. If the variance of the data is greater than a critical value, the data is stored with time information. Lowering the critical value would allow recording of weaker seismic waveforms, but it would also record various vibrations other than earthquakes, which could result in large amounts of data. The mean and variance of the data averaging over 30 minutes are also stored, and the process is repeated. The average value of acceleration corresponds to the angle data in the x-, y-, and z-axis directions. The program is written in Python and runs every hour at 0 and 30 minutes using the crontab function.

Raspberry Pi is connected to the Internet and the inclination angle, vibration, and seismic waveform data is sent to a separate server using PHP and FTP. This makes it possible to check the data anytime, anywhere.

IV. Experiments and Results

The experiment was conducted by setting up the apparatus near the center of the seventh floor of an eight-story building in Hitachi, Japan. A map of the experiment location is shown in Fig. 6.

Fig. 6. Map of the experiment location.

A. Measurement of Earthquake

Fig. 7 shows the vibration waveforms under normal conditions. Fig. 8 shows an example of waveform of an earthquake and its power spectrum. The standard deviation of the vibration data in the X and Y directions during normal conditions is about 0.09 gal, and that in the Z direction is about 0.14 gal. The earthquake waveform is that of a magnitude 6 earthquake that occurred on August 1, 2024, at 12:0 p.m. in Tokyo, Japan. The normal vibration waveform contains electrical noise and weak vibrations from the sensor. This value is the limit of the measurement. To lower the limit of measurement, it is necessary to install the device closer to the ground and to use a sensor with lower noise. However, since our objective is to see the response of the building to various external influences, it is preferable to install them on the middle floors and above.

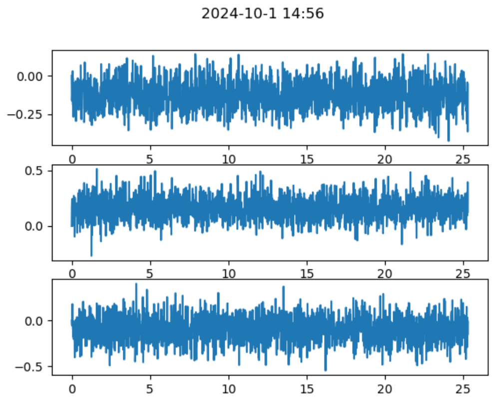
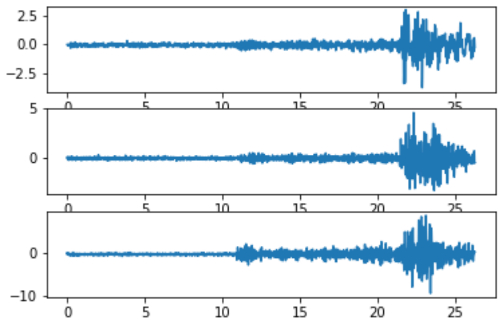
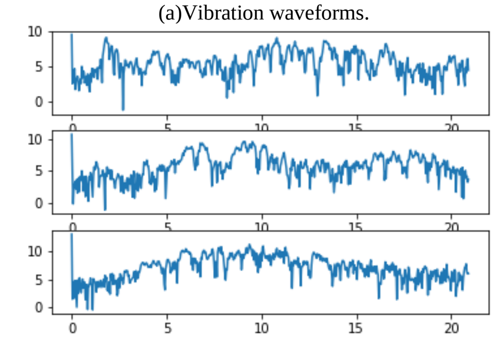


Fig. 7. Vibration waveforms under normal conditions.



(a)Vibration waveforms.



(b) Power spectrum.

Fig. 8. Vibration waveforms of earthquake and power spectrum.

B. Inclination Angles Measured by Two Methods

Inclination angles measured by two methods were compared. Fig. 9 shows an example of inclination angle measurement using a bubble tube. Fig. 10 shows an example of inclination angle measurement using an accelerometer. Although the angular variations were obtained using different methods, the general trend is consistent. The angle variation obtained by the accelerometer has a larger variation due to noise. The temperature dependence of the offset of ADXL355 is 0.15 mg/°C(Max). For example, a temperature change of 5°C results in a variation of 0.75 mg. This value corresponds to an angular variation of 0.04° degrees. When compared as an angle variation measurement device, the device using a bubble tube is a more stable method with less noise and less temperature dependence.

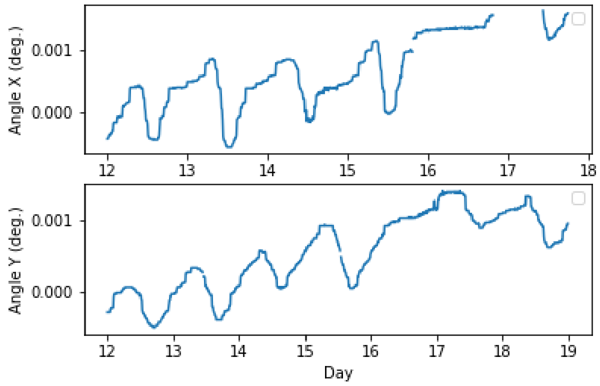


Fig. 9. Inclination angle measured by bubble tube.

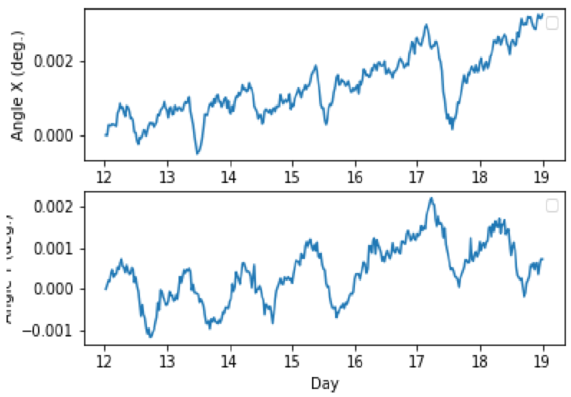


Fig. 10. Inclination angle measured by accelerometer.

C. Dayly Change of Inclination Angle

Figs. 11 and 12 show examples of the daily change of the inclination angle in the XY direction using a bubble tube, where Fig. 11 is for a sunny day and Fig. 12 is for a cloudy day. On a sunny day, the sun's movement causes the inclination trajectory to form a snarling ellipse. The amplitude of this trajectory is about 0.04 degrees. This is due to the expansion of the building surface where it is exposed to sunlight. This movement is also affected by the shapes of the buildings. On the other hand, on cloudy and rainy days, the inclination trajectory is small. Because the sunlight is diffused by the clouds.

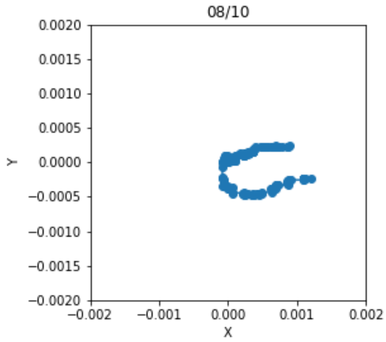


Fig. 11. Daily change of the inclination angle (Sunny day).

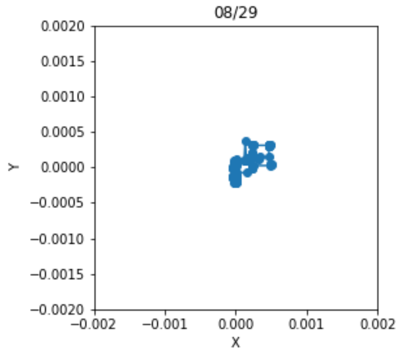


Fig. 12. Daily change of the inclination angle (Rainy day).

Fig. 13 shows an example of the daily change of the inclination angle in the XY direction using an accelerometer. The influence of noise is large, and the trajectory is not clear compared with the bubble tube method.

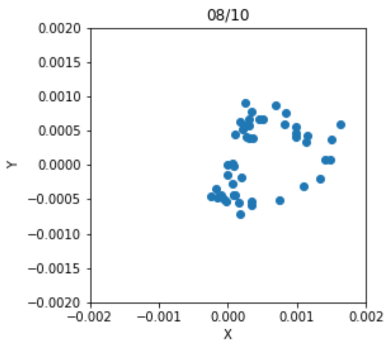
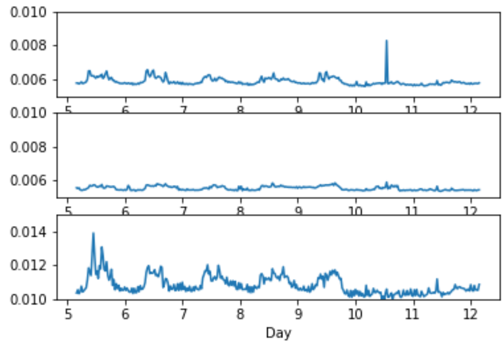


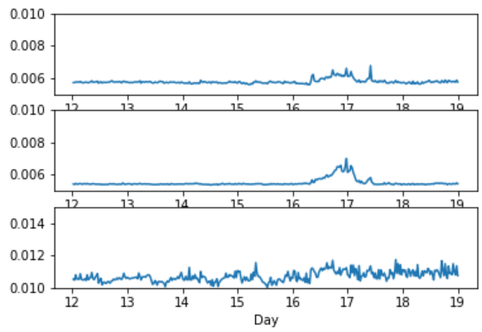
Fig. 13. Daily change of the inclination angle measured by accelerometer.

D. Vibration Measurement

Fig. 14 shows an example of vibration measurement using an accelerometer. The vibration is variance of acceleration over 30 minutes. The data from August 5 to 11 show that the vibrations are larger during the daytime on weekdays and smaller at night and on weekends. From August 12 to 16, the vibration level is low due to the restriction of entry to the site by the summer vacation. The peak of the X component on August 10 was caused by a magnitude 6.8 earthquake with an epicenter in the southern Sea of Okhotsk. There is a small peak on August 17. This was caused by the magnitude 4.5 earthquake that occurred off the coast of Miyagi Prefecture at 9:33 a.m. on August 17.



(a) From August 5 to 11.



(a) From August 12 to 16.

Fig. 14. Vibration data in X, Y and Z direction in two weeks.

V. CONCLUSION

Knowing the normal condition of a building, it is possible to diagnose damage to the building caused by a large earthquake. For this purpose, an inclination measurement device using a bubble tube and a vibration and inclination measurement device using an acceleration sensor were developed, installed in a mid-rise building, and evaluated. The inclination data obtained with the bubble tube and the accelerometer showed a similar trend. For angle measurement, we confirmed that the method using a bubble tube is more stable with less error. As reported in a previous paper, it is possible to diagnose building characteristics based on the correlation between weather and building angle change [15].

The method using acceleration sensors provided data on vibration waveforms caused by earthquakes and other events, as well as data on the vibration status of buildings. The seismic waveform data can be compared with nearby seismic waveform data to obtain building characteristics. The time-series vibration data provide information on human activities in the building. All these data indicate the characteristics of the building. When this data changes after a certain point in time, there is a possibility that some damage or other change has occurred in the structure of the building.

The method proposed in this paper can be used for monitoring in areas where landslides are expected. However, since the measurements will be made outdoors, it is necessary to consider temperature control, waterproofing, power supply, data communication, etc.

CONFLICT OF INTEREST

The author declares no conflict of interest.

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