Vibration measurement of KIUT building by MEMS accelerometer

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Abstract. This paper describes the measurements of structure small vibration in buildings of Yeoju Technical Institute in Tashkent (YTIT) in the use of MEMS accelerometer. The natural frequencies of main 6-story building were about 1.55Hz in both directions. In additions, the frequencies were measured for 10-story building under construction.

1 Introduction

Buildings have a natural period, and when shaking of this period is added, the movement increases. When motion becomes larger, the period generally lengthens, and beyond a certain limit of motion cracks occur, causing seismic damage. If the vibration amplitudes become larger, the residents will feel dangerous and the heavy damage will be induced. Therefore, it is necessary to understand the vibration of the building from the viewpoint of ensuring the safety of the building. The building is constantly oscillating with slight amplitude. Measuring this oscillation and knowing the vibration characteristics of the building is an useful way to obtain the safety measures of building as the first step.

Fig. 1 shows the relationship between the building height and the primary natural period shown by the Japan Meteorological Agency.

Fig. 1. Relationship between building height and first natural period shown by the Japan Meteorological Agency

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The building damages caused by strong winds and earthquakes have been written in histories from a long time ago. Attempts to measure the vibration of structures were made in the second half of the 19th century. According to Wikipedia, the modern seismograph was developed in Japan by the British James Alfred Ewing \[1\] and John Milne \[2\]. The 1880 Yokohama earthquake triggered the development of seismographs. Inspired by the 1880 Yokohama earthquake, they, with the cooperation of the Japanese, made a horizontal two-component disc recording seismograph using a horizontal pendulum. Here, the principle of the vibrometer is described \[3\].

A seismograph is a vibrometer that records the amount of movement of the pendulum position with respect to the pendulum spring mounting position, and uses that as the displacement, velocity, and acceleration of the pendulum mounting position. Assuming a pendulum, the period \(T_o\) of the pendulum is \(T_o = \frac{2\pi}{\sqrt{\ell / g}}\), \(\ell = 1\text{m}, g = 9.8\text{m/s}\)\(^2\), \(T_o = 2\text{sec}\). Then, for a long period \(T\) motion of 2 seconds or more, the position movement record of the pendulum draws a record proportional to the acceleration of the mounting position. For a short period \(T\) motion of 2 seconds or less, the pendulum position movement record draws a record proportional to the displacement of the mounting position. A record proportional to the velocity of the mounting position is drawn around 2 seconds. The equation of the seismograph (vibrometer) can be expressed as follows, which is drawn using trigonometric functions \(\omega_o = 2\pi f_o = \frac{2\pi}{T_o}\), \(h\) are the circular frequency and damping constant of the vibrometer.

\[
\ddot{x} + \ddot{y} + h\omega_o \dot{\omega}_o x + \omega_o^2 x = 0 \quad \text{we write} \quad x = X \quad \omega_o \dot{\omega}_o t \quad y = Y \quad \omega_o \dot{\omega}_o t
\]

\[
X = -\frac{-\omega_o}{\omega_o^2 - \omega^2 + h\omega_o \dot{\omega}_o} Y
\]

at \(\omega_o \ll \omega\) \(X = -Y\) at \(\omega_o \ll \omega\) \(X = -\frac{i\omega_o Y}{h\omega_o} \at \omega_o \gg \omega\) \(X = -\frac{\omega_o Y}{\omega_o}
\]

\[T < T_o \quad x = -\ddot{y}\] at \(T \approx T_o\) \(x = -\frac{T_o}{\pi \omega_o} \ddot{y}\] at \(T \gg T_o\) \(x = -\frac{\ddot{y}}{\omega_o}\n\]
When determining the natural frequency of a structure such as a building, an excitor is installed so that a force is applied to the building only in a predetermined direction. Then, forced vibration test with excitor is performed, and attempts are made to capture high-order natural vibration modes such as secondary and tertiary, and to generate free vibration by impact to obtain the damping constant. However, much labor and cost are required to install an excitor. For this reason, the number of excitor experiments has been reduced in recent years.

Coupled with the dramatic progress and spread of computer, communication, and miniaturization technology, the progress of measurement technology and analysis technology after World War II is surprising. An accelerometer is also housed in the smartphone. The recorded waveform of the vibration was previously drawn in soot, fixed, and seen. In the next step, the movement of the pendulum was electrically captured, then passed through an amplifier and analog filter, and then optically printed on photographic paper or written on a pen recorder. The electric signal was recorded on an analog magnetic tape. In the 1970s, the progress of AD converters became remarkable. Furthermore, the capacity of digital recording media has increased explosively, making it easier to record with a vibrometer. As an example, there is a MEMS accelerometer. One MEMS (microelectromechanical system) accelerometer has a resolution of 1 μG (0.001 cm / s²), and the size of a matchbox with a memory for long-term recording and a USB or power port or an accelerometer.

As we obtained several MEMS accelerometers recently, we tried to measure the vibration of the YTIT building and understand the vibration characteristics, so I will report the results. We carried out four measurements. In first measurement, we tried to get the building responses to input waves through ground. In second and third ones, reviewing first measurement results, we measured and analyzed high amplitude wave parts. In second measurement, accelerometers were distributed horizontally, and in third measurement, accelerometers were distributed vertically. In fourth measurement, the ten-story buildings under construction were measured simply.

2 Instruments

The MEMS accelerometer was made by NETPLUS Co. Ltd. in Japan using US elements. The accelerometer automatically starts measurements and records data when power is supplied. When using multiple accelerometers, run the cables for synchronization. However, in order to avoid cable wiring, before starting the measurement, all accelerometers were collected in one place to measure and record the impulse, and the power was not turned off after impulse measurement. From the impulse position, we adjusted the time axis during data analysis. Since the recording duration was short and the primary vibration of the building was targeted, the clock was not verified. One accelerometer has a memory capacity of 1G byte and records three acceleration components and temperature. The accelerometer can record continuously for 20 days with 100Hz sampling and one data 20-bit measurement. When the memory is full, the accelerometer will overwrite in sequence. If AA batteries are connected in series at a voltage of 6V, recording for about 2 weeks can be performed. The acceleration resolution is 0.005 cm / s². The maximum recording acceleration is about ±2.5G. Fig. 2 shows a photograph of the accelerometer.
3 YTIT Buildings

3.1 6 Story Buildings
reinforce concrete structures. Column cross sections have 40cm x 40cm. Wall is brick and thickness is the same as column width (40cm). Construction method of brick wall is estimated to be probably infilled, not confined masonry. It seems to be a stack of three bricks.

Figure 7 shows the accelerometer mounting position using a cross-sectional view and a photo.

Fig. 4. First Floor Plan of Main Building and Accelerometer Position in First, Second and Third Measurements

Fig. 5. Sixth Floor Plan on Main Building and Accelerometer Position in First, Second and Third Measurements
3.2 Two 10 Story Buildings
A rectangular area has an area of 17.4m x 30m. A small rectangular area has an area of 17.4m x 6m. A curved area has a fan shape plan. The open angle of the fan shape is 45 degrees. In the curved building, the ground adjacent to the south side of the rectangular building and the curved building (dotted line part in Fig. 9) is one floor higher than the ground on the north side of the curved building. Heights of two ten-story buildings are the same as 26.65m. In Fig. 9, the accelerometers distributions of the fourth measurement are shown.

Fig. 8. Ten Story Buildings, Rectangular Building (Left), Curved Building (Right)

Fig. 9. 10-Story Building Outline, and Accelerometer Distribution in Fourth Measurement

2020/11/29 (Sun) 13:12.

Fig. 10. Pulse records of first measurement
4 Measurements

Measurements were carried out four times. Measurements of first, second and third were for understanding vibration characteristics of a main 6-story building. Measurement of the fourth was for the same understanding at two 10-story buildings.

4.1 Measurements for YTIT Main 6-Story Building

The measurements for YTIT's 6-story building were conducted three times.

4.1.1 First Measurement

In the first measurement, attempts were made to obtain building responses to ground motions. Two accelerometers were used, one installed at the foot of the first floor column, and the other at the head of the sixth floor column. The positions of the accelerometers are indicated in Figs. 4, 5, 6, 7 with red dotted circles. Measurement continued for about 10 days. Pulses were found in recorded time histories. Fig. 10 is a record of pulses found in the column head of the sixth floor and in the column foot of the first floor. The record length is about 400 sec. The background noise is less than $\pm 2\text{cm/s}^2$. The pulse part was enlarged as shown in Fig. 11.

![Fig. 11. Enlargement of Pulse Part (time length 10:24 sec)](image)

According to Fig. 11, at a glance, the waves time history are clear to contain components of more than 10 Hz. If the recorded frequencies would be a whole scale building response, the responses would be too high frequency to understand. To obtain a whole scale building response, another time history part should be selected. However, pulse parts gave no whole scale building responses. But, big background noise parts caused by student movements provided building vibrations less than 5 Hz. Fig. 12 is time history transformed from acceleration to velocity, which was caused by student movements.
4.1.2 Second Measurement

After first measurement, four accelerometers were prepared. The main purpose of measurements is to understand a whole building vibrational characteristics. So, considering the results of first measurement, pulse parts in accelerometer records are considered not to be important. As mentioned above, YTIT main 6-story building was constructed in dividing three structures. Therefore, in second measurement, four accelerometer positions were installed and fixed with two side cohesive tape at each place of three divided structures on sixth floor and at one place on first floor. One accelerometer position is at the east side structure, others are at the central structure, and at the west side structure on the 6th floor, as shown in Fig. 4, 5, 6, 7 with circles filled by red color. Measurement continued 2 days from about 12 o’clock April 7.

4.1.3 Third Measurement

The purpose of third measurements is to obtain vertical vibration distribution of YTIT 6-story building. Four accelerometers were installed at column foot on 1st, 2nd, 4th and 6th floor in center structure part, as shown in Fig. 4, 5, 6, 7 with black circles. The measurement continue one day from 13 o’clock April 12, to April 13, 2021. YTIT building responses to student movements were about 2 cm/s².

4.1.4 Fourth Measurement

Fourth measurement was carried for two 10-story buildings. One building is called as rectangular building, the other is called as curved building. Two 10-story buildings were under construction. Frame structures were already completed. So, fourth measurement was simply conducted to measure natural frequencies. However, installation of accelerometers was hard with drilling and skewing to the concrete slabs. Four accelerometers were used in the measurement. Ground floor movements of two 10-story buildings were assumed to be same, one accelerometer was installed on first floor of curved building. And one accelerometer was installed on tenth floor in rectangular building. Two accelerometers were installed on tenth floor of large and small rectangular area in curved building. Fig. 9
presents the positions of accelerometers with \( A, B, C, D \). The measurement continued 3 days from 15 o’clock, May 21 2021 to May 24.

### 5 Data Analysis

The data after first measurement were performed the time integration and filtered with low frequency passing filter (low pass filter) and high frequency passing filter, as data processing preparation. The data were converted to velocity by onetime integral over time, and proceed with the analysis to make the waveform with a frequency lower than the acceleration conspicuous. Since the measurement record contains some errors, there is a tendency for divergence when integrated. Therefore, a high-pass filter is used. Here, the simple formula

\[
\frac{x_{o}(i) - x_{o}(i-1)}{dt} + q \cdot x_{o}(i) = \frac{x_{i}(i) - x_{i}(i-1)}{dt},
\]

\( x_{i}(i) \): input, \( x_{o}(i) \): output, \( q = 2\pi \cdot f_{c}, f_{c} \): cut off frequency, \( dt \): step interval time, \( i \): step count. The low-pass filter is also calculated by the old formula

\[
\frac{x_{o}(i) - x_{o}(i-1)}{dt} + 2\pi \cdot f_{c} \cdot x_{o}(i) = 2\pi \cdot f_{c} \cdot x_{i}(i).
\]

Fig. 13 shows the acceleration records on the 1st and 6th floors, Fourier Spectra, and Fourier Spectra Ratio. A 1Hz high-pass filter and a 20Hz low-pass filter are passed once. If looking at the Fourier Spectra, it can see that the filters were applied at 1Hz and 20Hz, but the Fourier Spectra Ratio was not affected by the filter. The influence of the cut off frequency of the filter and the number of iterations of the filter appears clearly in the waveform and its amplitude, but it is considered that there is no influence on the frequency and amplitude ratio. No filtered waveform was shown in Fig. 14. Waveforms with 1Hz and 0.5Hz high-pass filters are also shown in Fig. 14. The iteration effects are understood also in Fig. 14.
5.1 Main 6-story Building Data

5.1.1 Analysis of Pulse like data

![Graphs showing spectral analyses for pulse like data parts](image)

**Fig. 14.** Filtering (cut off frequency) and iteration Effects

**Fig. 15.** Spectra of X, Y, Z components of 3 pulse like data at 1st F.
Fig. 16. Spectra of X, Y, Z components of 3 pulse like data at 6th F.

The spectra data of pulse like record parts at 1st and 6th floor shows no peaks in less than 5Hz. According to analysis for pulse like data parts in background noise (2cm/s^2), 1st natural vibrations were not found.

5.1.2 Analysis of Big Background Noise Parts

Horizontal Distribution) Big background noise parts recorded soon from starting measurement was analyzed with Fourier spectra. Analysis data length was 40.96 seconds. As mentioned above, at first, three accelerometers were distributed horizontally over 6th floor at three locations: the east side building position, the central building position, and the west side building position in addition to base accelerometer of the 1st floor. 1st floor data Fourier spectra of three component are shown in Fig.17. Fourier spectra and Fourier spectra ratio 6F/1F of waves in two horizontal directions are shown in Fig.18 and 19. Here, the average value of the entire recording area of the measured acceleration recording was removed to obtain the zero line of the measured acceleration recording, and then the velocity wave was obtained by integrating once with respect to time. Further, the velocity wave was passed through a 1 Hz high-pass filter and a 20 Hz low-pass filter to obtain the wave shown here, and Fourier analysis was performed on this wave. The Fourier spectra ratios at each 6th floor accelerometer to 1st Fourier spectra shows a peak frequency around 1.55 Hz. The amplitude of the building on the east side is slightly smaller in both directions parallel and right to the road.
Fig. 17. First floor velocity waves and Fourier spectra at 2nd measurement.

Fig. 18. X Spectra of East side, Central, West side part in 6F.
Fig. 19. Y Spectra of East side, central, West side part in 6F.

Fig. 20. Horizontal Tracing Loops of 3 positions in 6F and 1F. Fig. 20 is a tracing loops in two horizontal directions, and the same characteristics can be seen. Fig. 21 is a wave and Fourier analysis of up-down component. A gentle mountain
Vertical Distribution) As for vertical vibration distribution, as the same as in the case of mentioned above, the analysis was performed focusing on the big background noise parts where the acceleration amplitude level is large without being caught by the shocking part.

The Fourier analysis time length is 40.96 sec. soon after the measurement starting. As mentioned above, there were four measurement points: the 1st floor, the 2nd floor, the 4th floor, and the 6th floor. The position is along the column in Fig. 5, 6, 7, 8. Property of the 1st floor was the same as before. Fig. 22, 23 are the Fourier spectra and Fourier spectra ratio to 1st floor for the parallel direction to the road (Y) and the right direction to the road (X). The natural frequency is almost the same in both directions and is around 1.55 Hz. The Tracing Loop in the horizontal plane of the 6th, 4th, 2nd, and 1st floors is shown in Fig. 24. The displacement distribution for each floor at this frequency of the Fourier Spectra Ratio is shown in Fig. 25. Based on the 1st floor, the magnification of the 6th floor is 26 times in Y direction and about 15 times in X direction.

Fig. 22.

Fig. 23.
5.1.3 New 10-Story Building Simple Measurement Datas

As already mentioned, vibrations were measured in 10-story rectangular building and 10-story curved building under construction. Measurements were taken for 3 days with one accelerometer on the 10th floor in a rectangular building and each accelerometer on the 10th floor of two rectangular area in a curved building, and an accelerometer on the first floor of a curved building. For the analysis, the spectra analysis of the Back Ground Noise section was performed in the same manner as before. First, looking at the predominant frequency of rectangular buildings, as shown in Fig. 26, there was a peak of 1.3 Hz (period 0.77 sec) in the long building axis and 1.4 Hz (period 0.71 sec) in the short building axis. As shown in Fig. 27, the predominant frequency in the long building axis of the large rectangular area of the curved building was 1.25 Hz (period 0.8 seconds) in long building axis, and 1.5 Hz (0.67 sec) in the short building axis. Referring Fig. 9, the curved building has the curve angle of 45 degrees, and the axis of the small rectangle area is at an angle of 45 degrees with respect to the axis of the large rectangle area. Due to this axis rotation effect, there are two peaks of 1.25Hz and 1.5Hz measured on the axis of the large rectangle area in the long building axis and the short axis building of the small rectangle area as it can be seen from Fig. 28. Further measurements are planned for the 10-story building.
6 Conclusions
measurement can be done with the Smart Phone, but from the viewpoint of ease of use, we think that this kind of device specialized for measurement will also be useful. It was cleared that the natural frequency of the YTIT main building was around 1.55 Hz in both horizontal directions, and it was found that the eastern vibration of the three structures separated by expansion was little bit small. The vertical distribution of vibrations was measured, and the results were almost the same as those of ordinary buildings. YTIT 10-story buildings which are currently under construction, were simply measured. YTIT 10-story buildings consisted of a rectangular building which has frequency 1.3Hz in long building axis, frequency 1.4Hz in short building axis, and a curved building which has frequency 1.25Hz in long building axis and 1.5Hz in short building axis for large rectangular area. As for the small rectangular area of curved building, spectra peaks were combined with peaks of long and short building axes of large rectangular area. Spectra of curved building data show that spectra of large area part effected the spectra of small area part. Further measurement and analysis for 10-story curved building will be continued.

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References