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 curve 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

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

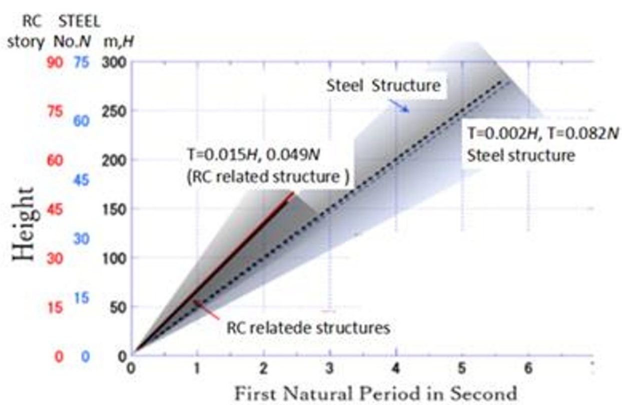

Fig. 1. Relationship between building height and first natural period shown by the Japan Meteorological Agency

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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 $T_o = 2\pi\sqrt{(\ell / g)}$, $\ell = 1$m, $g = 9.8$m / s^2, To = 2sec. 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 and complex numbers. $\omega_o = 2\pi f_o = 2\pi / T_o$, h are the circular frequency and damping constant of the vibrometer.

$$\ddot{x} + \ddot{y} + 2h\,\omega_o\,\dot{x} + \omega_o{}^2 x = 0, \qquad \textit{we write} \quad x = X\ \exp(i\ \omega t), \quad y = Y\ \exp(i\ \omega t)$$

$$X = -\frac{-\omega^2}{(\omega_o{}^2 - \omega^2 + 2h\,\omega_o \omega i)} Y, \tag{1}$$

$$at\ \ \omega_o \ll \omega\ \ X = -Y,\ \ at\ \omega_o \fallingdotseq \omega^2\ \ X = -\frac{1}{2h\,\omega_o} i\omega Y,\ \ at\ \ \omega_o \gg \omega\ \ X = -\frac{1}{\omega_o{}^2}(-\omega^2 Y)$$

$$\Downarrow$$

$$T \ll T_o \quad x = -y,\ \ at\ T \fallingdotseq T_o\ \ x = -\frac{T_o}{2\pi \cdot 2h}\dot{y},\ \ at\ \ T \gg T_o \quad x = -\frac{1}{\omega_o{}^2}\ddot{y}$$

As it can be seen from this equation, it is difficult to miniaturize the displacement vibrometer, but the accelerometer can be miniaturized as much as possible if the pendulum movement of sensor is miniaturized and the sensitivity is increased. For example, if a vibrometer with a frequency of 500 Hz measures 2G acceleration, the movement of the pendulum of the accelerometer will be 2μ. An accelerometer with a strain gauge attached to the pendulum spring was called a dice. This indicates that the accelerometer is small.

After the 1905 San Franco earthquake, Stanford University [4] built and experimented with a mechanical shaking table. Naturally, it is considered that the vibration measurement was performed at that time. In addition, the need for strong motion observation was recognized, and acceleration was recorded in 1933 Long beach earthquake [5].

Many five-storied pagoda have been built in Japan from a long years ago, and many people were interested in how the earthquake response [6-7]. One of them is the five-storied pagoda of Nikko Shogun Shrine. Looking at the column on the fifth layer, there is a notation of "February 28, 1919, March 1, 1919, Doctor of Science, Fusayoshi Omori, Vibration Test" (first natural frequency 0.8 Hz). In recent years, for famous structures of the world, vibration measurements and earthquake response observations have been conducted. The Eiffel Tower, in recent years, the vibration characteristics has been measured and analyzed, and the first frequency of 0.32 Hz is shown [8]. Tokyo Tower of nearly same height has the first natural frequency of 0.38Hz [9].

When determining the natural frequency of a structure such as a building, a 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 a 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 a example, there is a MEMS accelerometer. One MEMS (micro-electromechanical system) accelero-meters have a resolution of 1 μG (0.001 cm / s^2), 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 4 are connected in series at a voltage of 6V, recording for about 2 weeks can be performed. The acceleration resolution is 0.005 cm / s ^{2}/. The maximum recording acceleration is about ± 2.5G. Fig.2 shows a photograph of the accelerometer.

Fig. 2. MEMS Accelerometer and AA Battery

Fig. 3. YTIT building site location

3 YTIT Buildings

As show in Fig, 3, Yoeju Technical Institute in Tashkent (YTIT) site locates at south side very near from Tashkent South Station. East side of YTIT is rail way. West side faces to wide road. Facing the road, YTIT main building of six story exists. Two 10-story buildings are under construction at the southeast side of the main building. At dates of measurement, the frame structures have already completed. One has a curved plan and the other has a rectangular plan.

3.1 6 Story Buildings

Fig.4, 5, 6, 7 are outlines of main building with accelerometer distributions of first, second and third measurements. The main building has one basement floor and six floors. The main building is structurally divided into 3 buildings by expansion joints. Plan is 72m (12 spans) x 48m (8 spans), total height is 29.1m. Columns, beams, floors, underground walls are 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.

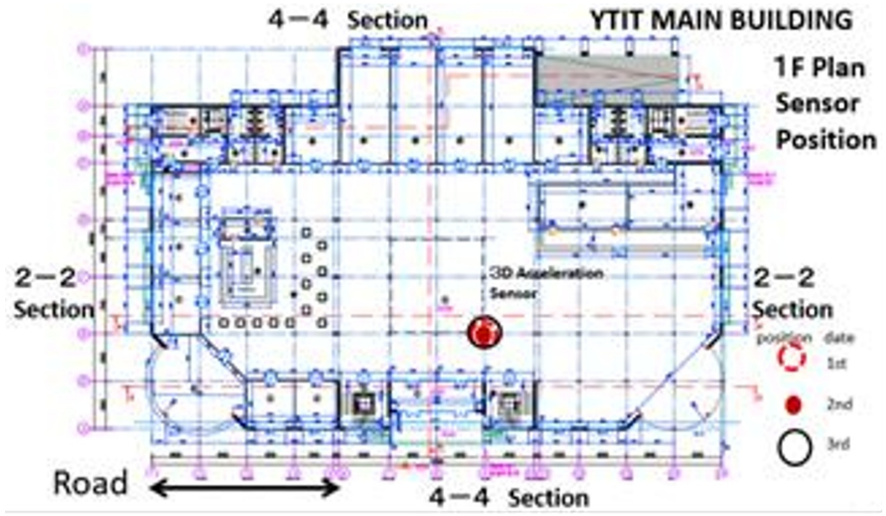

Fig.4. First Floor Plan of Main Building and Accelerometer Position in First, Second and Third Measurements

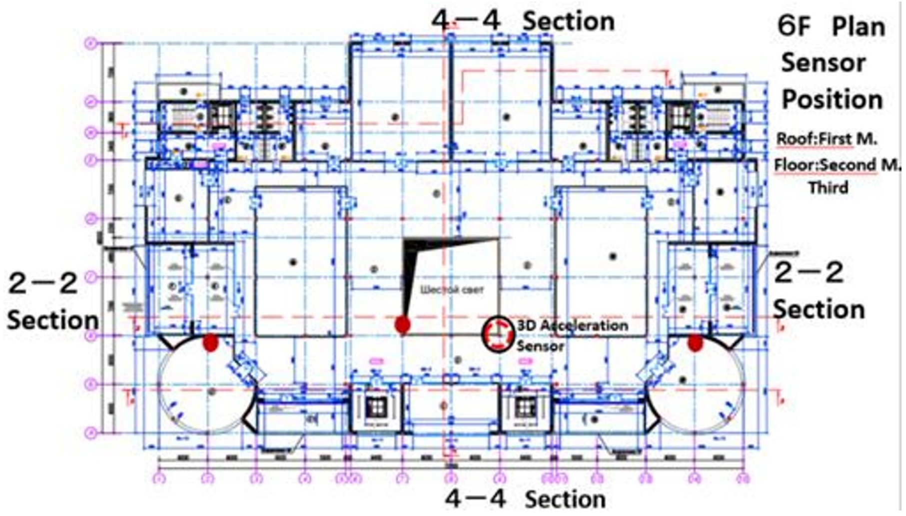

Fig. 5. Sixth Floor Plan on Main Building and Accelerometer Position in First, Second and Third Measurements

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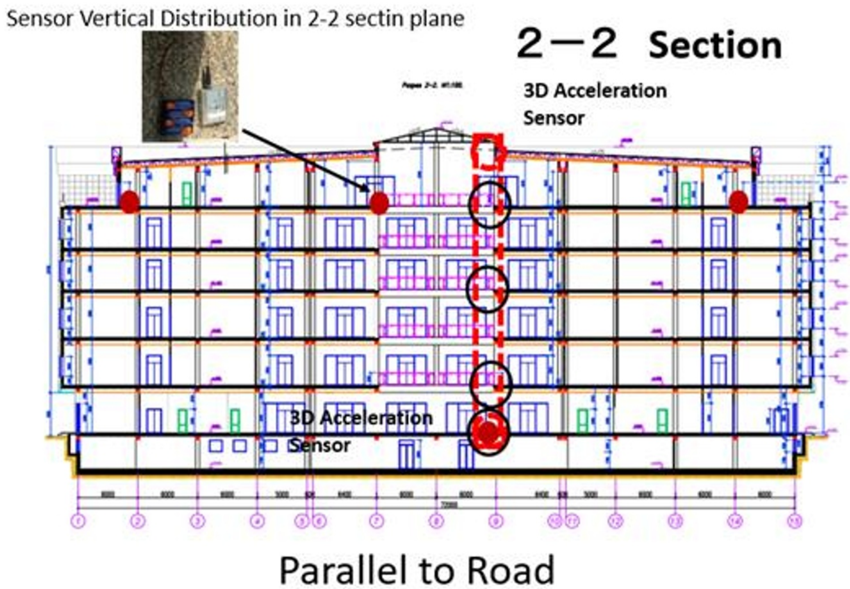

Fig. 6. Section Elevation (along 2-2 line) of Main Building and Accelerometer Position in First, Second, third Measurement

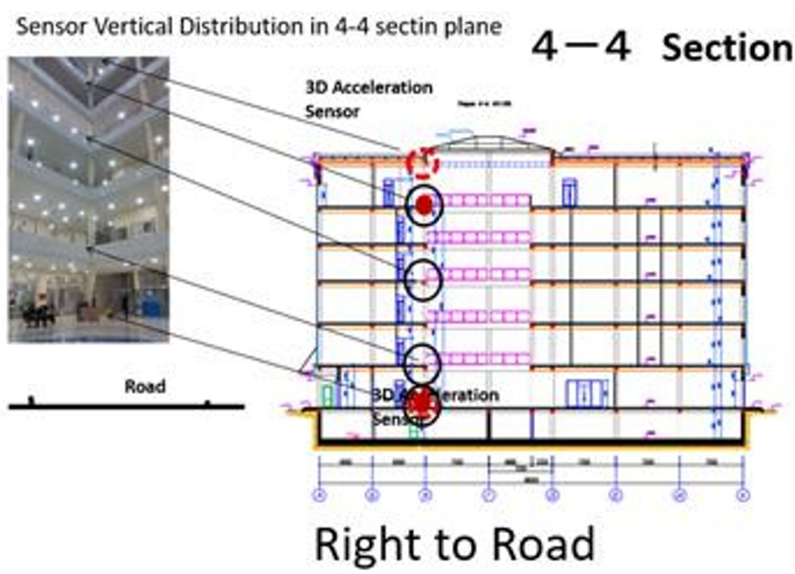

Fig. 7. Section Elevation (along 4-4 line) of Main Building and Accelerometer Position in First, Second, third Measurement

3.2 Two 10 Story Buildings

Fig. 8 is a photo of north side view for two 10-story buildings under construction. Two buildings have basements. Rectangular building has a plan of 29.4m x 18m. Curved building has two rectangular plans and one curved plan, as shown in Fig. 9. A large rectangular area has area of 17.4m x 30m. A small rectangular area has area of 17.4m x 6m. A curved area has a fan shape plan. The open angle of fan shape is 45degree. 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 building are same as 26.65m. In Fig.9, accelerometers distributions of fourth measurement are shown.

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

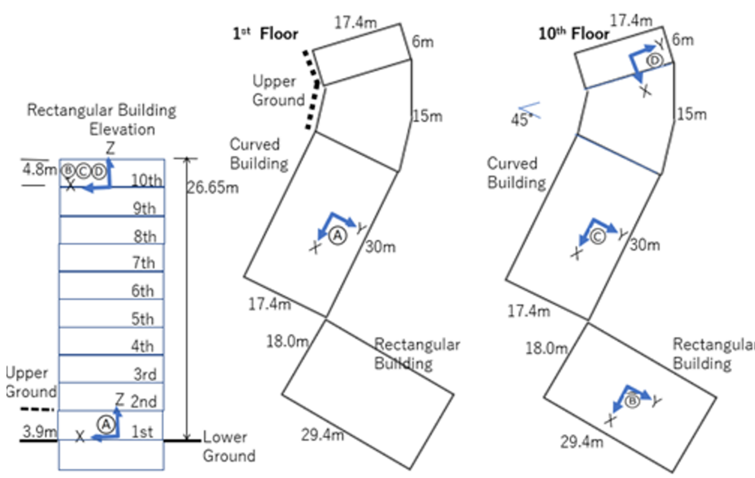

Fig. 9. 10-Story Building Outline, and Accelerometer Distribution in Fourth Measurement

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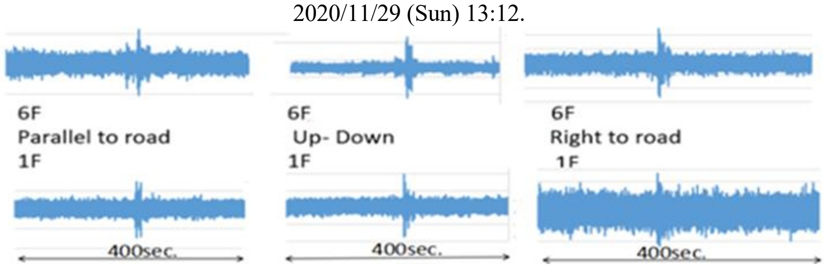

Fig.10. Pulse records of first measurement

4 Measurements

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

4.1 Measurements for YTIT Main 6-Story Building

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

4.1.1 First Measurement

In first measurement, building responses to ground motions tried to be obtained. Two accelerometers were used. One was installed at column foot of first floor, the other was at the column head of sixth floor. Positions of accelerometers were indicated in Fig.4,5,6,7 with red dotted circle. Measurement continued about 10 days. Pulses were found in recorded time histories. Fig.10 is a record of pulses which were found in column head of sixth floor and in column foot of first floor. The record length is about 400sec. The back ground noise is less than ±2cm/s^2. Pulse part was enlarged as Fig.11.

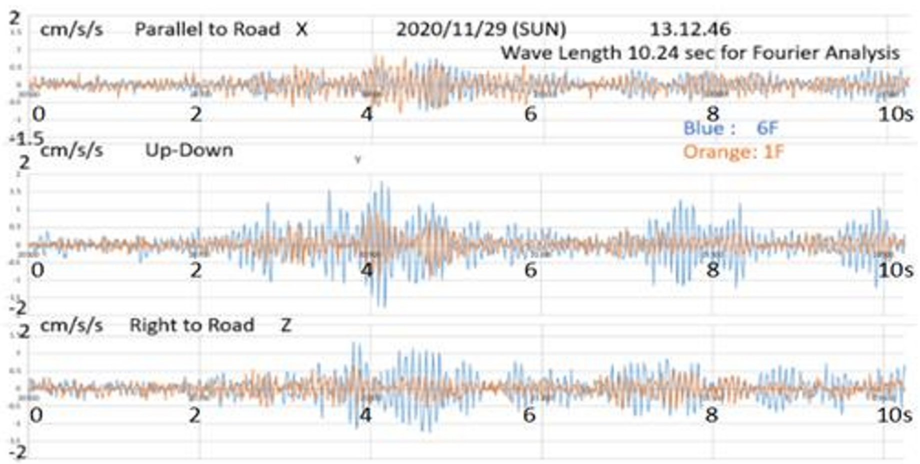

Fig. 11. Enlargement of Pulse Part (time length 10:24 sec)

According to Fig.11, at glance, the waves time history are clear to contain components of more than 10Hz. 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 back ground noise parts caused by student movements provided building vibrations less than 5Hz. Fig 12 is time history transformed from acceleration to velocity, which was caused by student movements.

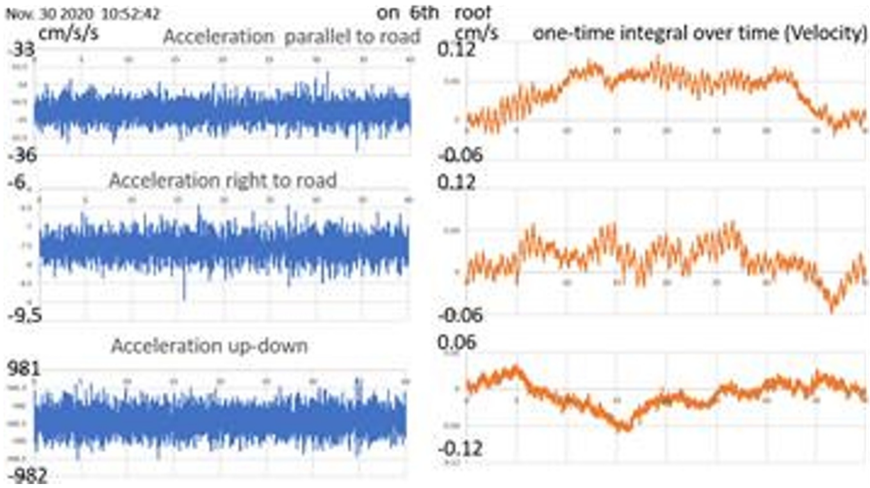

Fig. 12. Recorded Acceleration and one tine integral over time (velocity), time length 40 sec

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 2days 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/s^2 .

4.1.4 Fourth Measurement

Fourth measurement was curried for two 10-story buildings. One building is called as rectangular building, the other is called as curved building. Two 10-story buildings was 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, May21 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 (high pass filter), as data processing preparation. The data were converted to velocity by onetime integral over tome, 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 $(x_o(i) - x_o(i-1)) / dt + q * x_o(i) = (x_i(i) - x_i(i-1)) / dt$, $x_i(i)$: input, $x_o(i)$: out-put, $q = 2\pi \cdot f_c$, f_c: cut off frequency, dt: step interval time, i: step count. The low-pass filter is also calculated by the old formula $(x_o(i) - x_o(i-1)) / dt + 2\pi \cdot f_c * x_o(i) = 2\pi \cdot f_c * x_i(i)$. 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.

In the data analysis of the 2nd and 3rd measurements, data were converted to velocity by above mentioned integral, and the data were performed filtering through the 1Hz high-pass filter and the 20Hz low-pass filter.

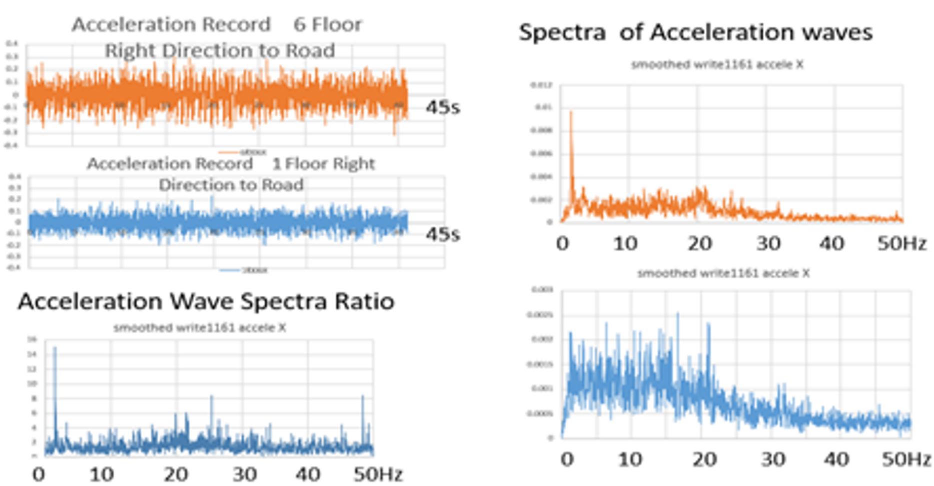

Fig. 13. Acceleration waves and Filtering effects in Fourier analysis

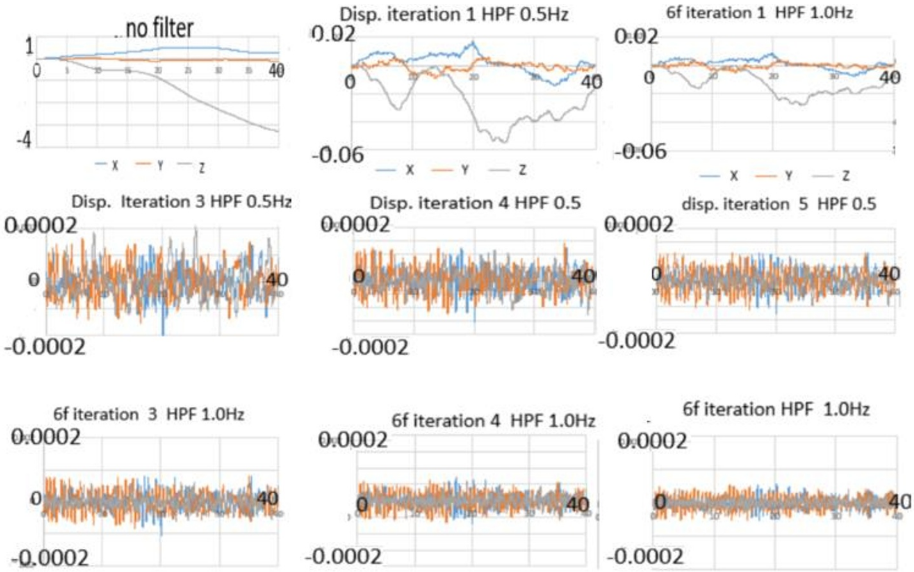

Fig. 14. Filtering (cut off frequency) and iteration Effects

5.1 Main 6-story Building Data

5.1.1 Analysis of Pulse like data

Pulse like data parts as shown in Fig.10 were recorded in first measurement. Spectral analyses for some pulse like data parts were performed as shown in Fig.15,16.

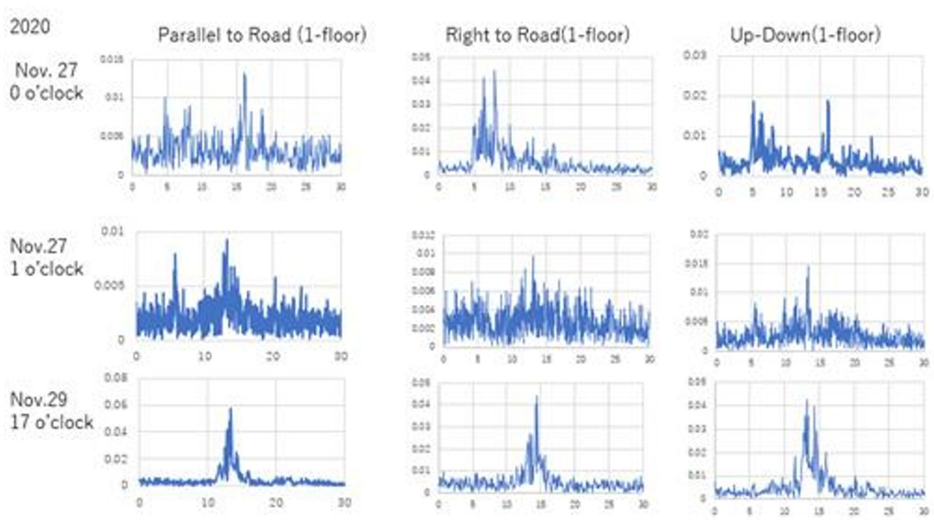

Fig. 15. Spectra of *X, Y, Z* 3 comp. of 3 pulse like data at 1st F.

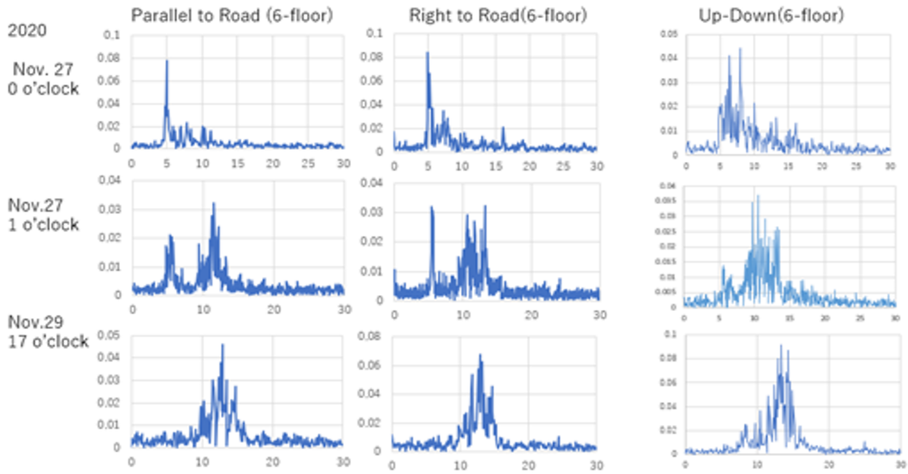

Fig. 16. Spectra of *X, Y, Z* 3 comp. of 3 pulse like data at 6th F.

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 back ground noise (2cm/s^2) , 1st natural vibrations were not found.

5.1.2 Analysis of Big Back Ground Noise Parts

Horizontal Distribution) Big back ground 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 Fourie 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.

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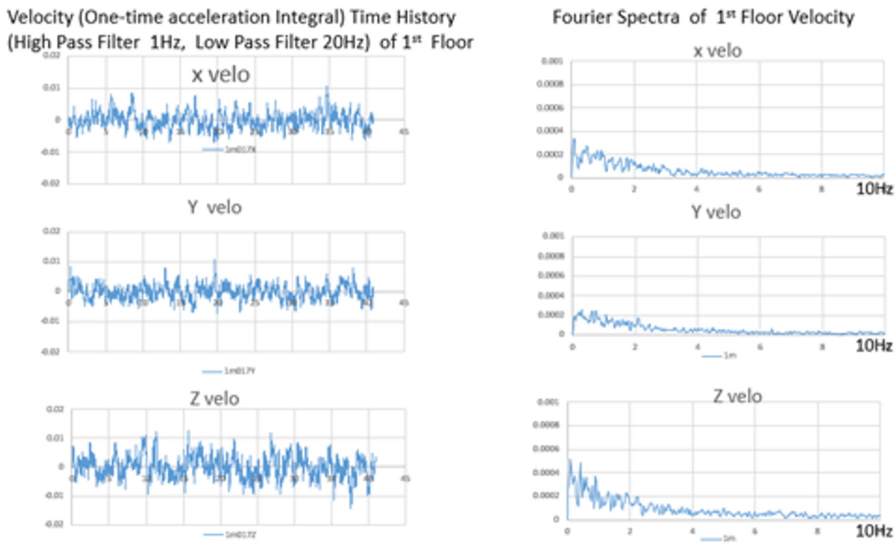

Fig. 17. 1st floor velocity waves and Fourier spectra at 2nd measurement

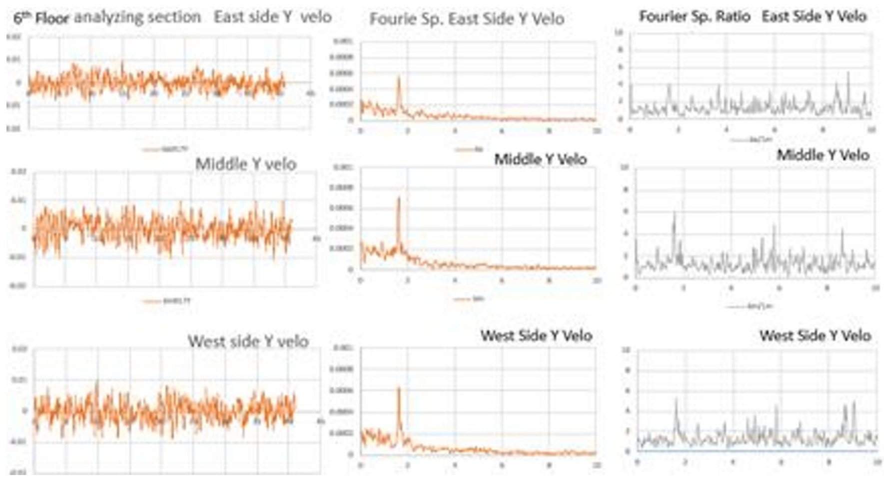

Fig. 18. X Spectra of East side, Central, West side part in 6F

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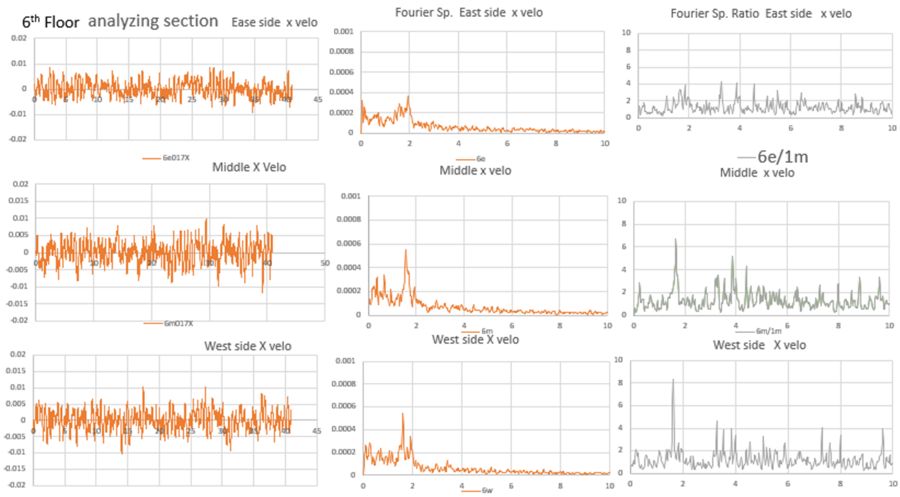

Fig. 19. Y Spectra of East side, central, West side part in 6F

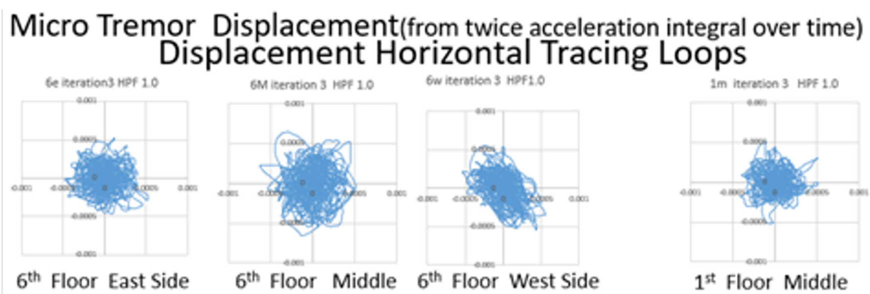

Fig. 20. Horizontal Tracing Loops of 3 positions in 6F and 1F.

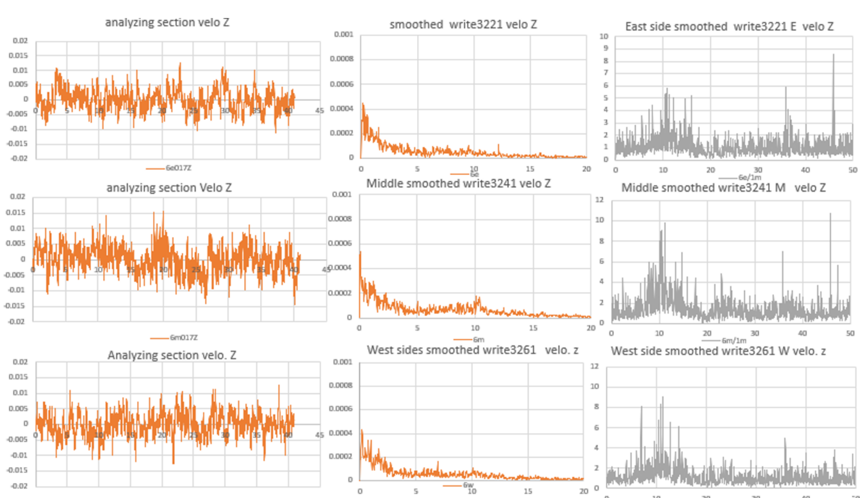

Fig. 21. Up-down component Spectra Analysis

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 (magnification of about 2) can be seen around 10Hz.

Vertical Distribution) As for vertical vibration distribution, as the same as in the case of mentioned above, the analysis was bperformed focusing on the big back ground 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.

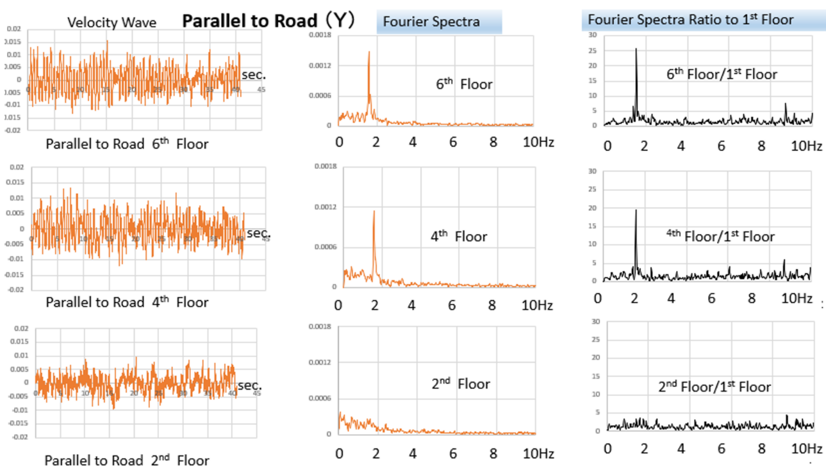

Fig. 22. Fourier analysis of 2 nd, 4th, 6th floor in Parallel to Road

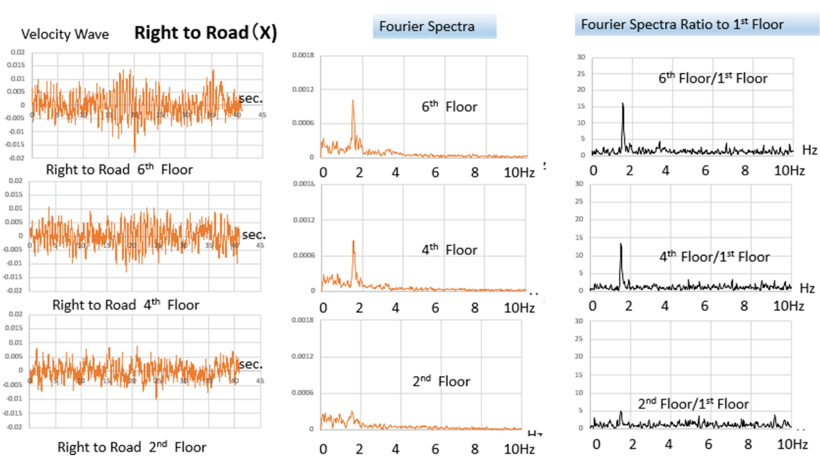

Fig. 23. Fourier analysis of 2nd, 4th, 6th floor in Right to Road

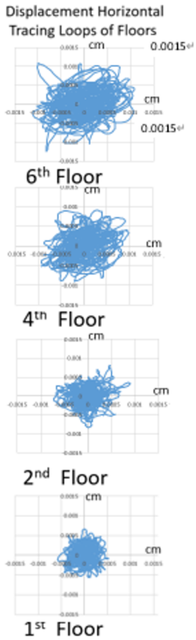

Fig. 24. Tracing Loops

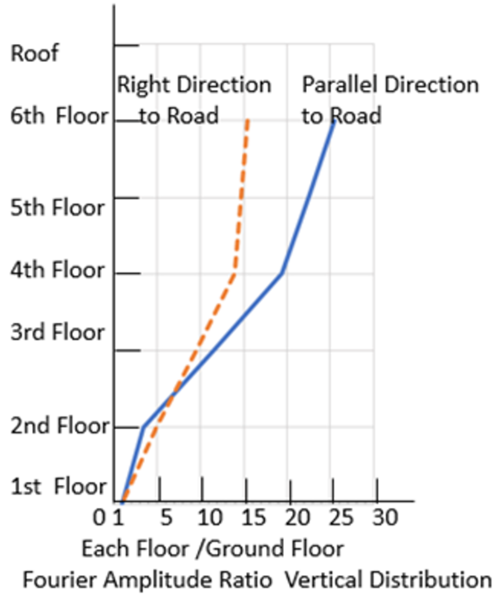

Fig. 25. Vertical distribution of two horizontal vibrations

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 on both building axes of the small rectangle area as it can be seen from Fig.28. Further measurements are planned for the 10-story building.

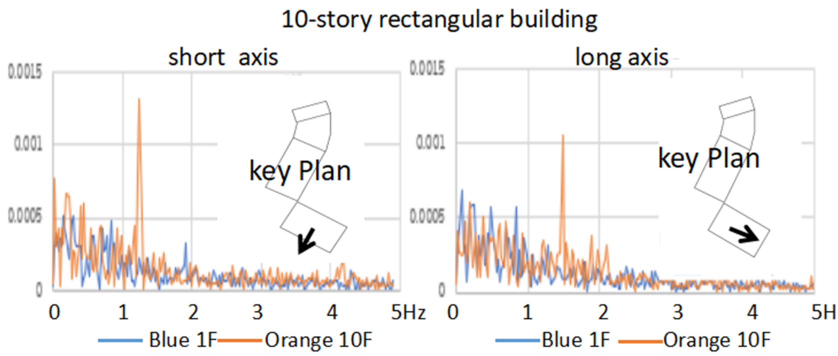

Fig. 26. Spectra of 10st floor data in long and short building axes of 10-story rectangular building

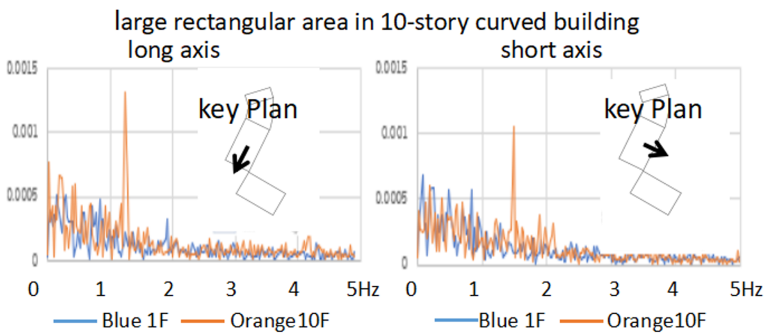

Fig. 27. Spectra of 10st floor data in long and short building axes of large rectangular area in 10-story curved building.

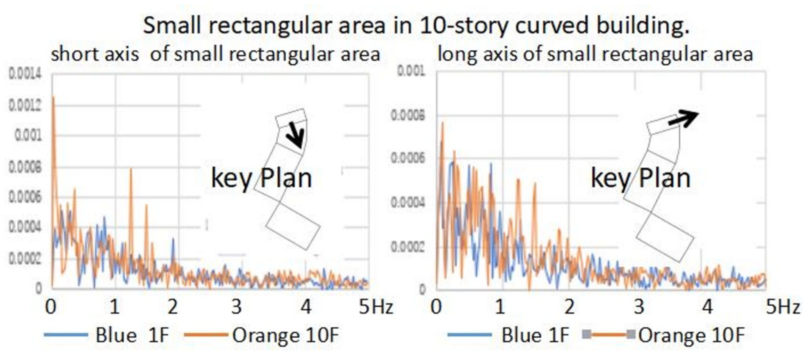

Fig. 28. Spectra of 10st floor data in long and short building axes of short rectangular area in 10-story curved building

6 Conclusions

The 4 times accelerometer measurements were carried out for the purpose of understanding the vibration characteristics of the YTIT main building of 6 story. The accelerometer used was a 6V drive with three components, a resolution of 0.005 cm / s^2, a maximum measured acceleration of 2.5 G and a storage capacity of 1Gbyte, and the price was about $ 300. Now that the Smart Phone has a similar MEMS accelerometer, it seems that the same 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.

Acknowledgment

Authors dedicate our special thanks to Mr. Yasushi Niitsu; Professor of Tokyo Denki University for his developing MEMS accelerometer and preparation of MEMS accelerometer for our measurement.

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