The Seventh Asian-Pacific Symposium on Structural Reliability and Its Applications (APSSRA2020)
October 4–7 2020, Tokyo, Japan
T. Takada, I. Yoshida & T. Itoi (editors)

IoT Based Structural Seismic Monitoring: System Development and Experimental Verification

R. Zuo[1], J. Dang[2], C.S. Goit[3], K. Shimizu[4], A. Tsunoda[5], and Y. Suzuki[6]

[1]*Staff, Kawakin Core-Tech Co., Ltd., r-zuo@kawakinkk.co.jp*
[2]*Assistant Professor, Saitama University, dangji@mail.saitama-u.ac.jp*
[3]*Assistant Professor, Saitama University, chandra@kiban.civil.saitama-u.ac.jp*
[4]*General Manager, Kawakin Core-Tech Co., Ltd., k-shimizu@kawakinkk.co.jp*
[5]*Deputy Manager, Kawakin Core-Tech Co., Ltd., tsunoda@kawakinkk.co.jp*
[6]*Assistant Manager, Kawakin Core-Tech Co., Ltd., y-suzuki@kawakinkk.co.jp*

Abstract: In disasters, such as large earthquakes, the rational and in-time response is derived from real-time and organized information. During post-earthquake assessments, bridges are one of the critical infrastructures for recovering the transportation functions in stricken areas. Though Structural Health Monitoring (SHM) systems have been installed all over the world to collect valuable service status information of bridges for many years, it is difficult to analyze those data in real time without the confirmation of various stakeholders. To densely collect real-time structural information, low-cost sensing devices are necessary to spread sensing networks to more structures. The Internet of Things (IoT) based Structural Seismic Monitoring (SSM) system is becoming more appealing in recent years. An IoT based SSM system is proposed in this study. The measurement unit mainly consists of a 3-axis ADXL355 MEMS accelerometer and a Raspberry Pi 3 Model B+ single-board computer. The measurement system was developed under Python open-source environment to handle data acquisition, data storage, and data transfer in the real time. Feasibility and measurement accuracy were verified through the shaking table tests with reference servo velocity seismometer VSE-15D. The raw sampling rate of the measured data shows a stable value of 100 Hz with standard deviation less than 1 Hz. Experimental results show a satisfactory agreement between the reference sensor and the IoT sensor in both time and frequency domains. A prototype was installed at a 10-storey building to monitor structural seismic response for long term. Records from four observed seismic events show that seismic events can be recognized easily even when the seismic intensity scale is just 1 as per the classification of the Japan Meteorological Agency (JMA).

Keywords: Structural Seismic Monitoring, IoT, MEMS, Raspberry Pi, Shaking table tests

1. Introduction

In the 2011 Great East Japan Earthquake, the logistics for delivering critical supplies to assist the people in need were significantly affected by the uncertainty of infrastructure conditions (Veras et al. 2014). Bridges perform as one of the key infrastructures to recover emergency logistics function for evacuation and rescue; to monitor the response of bridges during earthquake is valuable (Padgett and Desroches 2007). Though structural health monitoring (SHM) system can provide valuable service status information of bridges, only some important bridges in a very limited numbers can afford SHM system (Thomson 2013). Universally, the bridge emergency inspection is carried out after earthquakes happen, but there are difficulties to carry out urgent safety inspection considering the complex situation in the aftermath of an earthquake (García 2012). The safety of inspectors cannot be ensured when they approach the structure and carry out the inspection. On the other hand, the time cost could be very high from inspection to decision making.

In the recent decades, study on real-time earthquake engineering has been paid a tremendous attention considering the damages due to disaster and the benefits emergency response can bring (Allen et al. 2009). In the field of disaster prevention and mitigation, it is necessary to understand the structural real-time response and the process of damage occurring, then corresponding countermeasures can be taken to minimize the future earthquake damages and a better seismic design method can be brought up. For facilitating the process of real-time seismic response analysis, the straightforward solution is to deploy long-term vibration monitoring instruments in structures.

The IoT sensing based SSM system is becoming more appealing in recent years as an innovative option. An IoT ecosystem consists of web-enabled smart devices that use embedded processors, sensors, and communication hardware to collect, send, and act on data they acquire from their environments; it has evolved from the convergence of wireless technologies, MEMS, and the internet. For the IoT sensing based SSM system, it comes with low cost, small size, low power consumption, and programmability. Through broad deployment of the IoT sensing based SSM system, unprecedented huge volume of ground motion data and structural response data will be available to promote the understanding of the structural dynamic behavior and the potential damage in structures under seismic loading.

A low-cost, high-accuracy, long-term, and real-time acceleration monitoring system is proposed in this study. The measurement unit mainly consists of a 3-axis ADXL355 MEMS accelerometer and a Raspberry Pi 3 Model B+ single-board computer. Though the data quality in the aspects of sampling rate and data integrity is often ignored in most of the IoT projects where high-frequency sampling is not necessary, such are mandatory for carrying out analysis in the fields of structural and earthquake engineering. In this study, the raw sampling rate achieved at 100 Hz was stable with standard deviation less than 1 Hz with no packet loss of uploading measured data to the cloud. The measurement system was developed under Python open-source environment to handle data acquisition, data storage, and data transfer in the real time.

Feasibility and measurement accuracy were verified through the shaking table tests with reference servo velocity seismometer VSE-15D (Tokyo Sokushin, 2010). Experimental results show a satisfactory agreement between the reference sensor and the IoT sensor in both time and frequency domains. A prototype was installed at a 10-storey building to monitor structural seismic response for long term. Records from four observed seismic events show that seismic events can be recognized easily even when the seismic intensity scale is just 1 as per the classification of the Japan Meteorological Agency (JMA).

2. IoT sensing based SSM system

The measurement unit consists of a single-board computer Raspberry Pi 3 Model B+, an uninterruptible power supply (UPS) power bank, and a 3-axis MEMS accelerometer sensor ADXL355 as shown in Fig. 1.

The single-board computer is a credit card-sized motherboard, whose on-board computation capability is far more powerful than that of a microcontroller. Its compact size means the requirement for the installation room is very tolerant. The function of this single-board computer is an independent node talking to the Internet directly as long as the Internet access is supplied, its throughput capacity of data transmission satisfies the demand of real-time monitoring data transmission. The Raspberry Pi 3 Model B+ can synchronize its clock to Network Time Protocol (NTP) servers, which makes sure the data recorded on separate devices can be synchronized in order to do further data processing.

The 3-axis MEMS accelerometer sensor ADXL355 is a low noise, low drift, low power 3-axis accelerometer with digit output, which the Raspberry Pi 3 Model B+ can read directly. The ADXL355 accelerometer provides selectable measurement ranges, it supports the ±2.048 g, ±4.096 g, and ±8.192 g ranges. The output data rate (ODR) of ADXL355 is 500 Hz, which is sufficient for structural seismic response monitoring purpose. The UPS is a power bank to ensure the power supply will not be affected by sudden power failure. The power bank is always fully charged when the power supply is normal, it will automatically become a power supply to supply power to devices for several hours when the original power supply is cut off. A water and dustproof case shown in Fig. 1 was prepared for on-site tests.

The system was developed by Python language. Inter-Integrated Circuit (I2C) protocol was used for communication between the single-board computer and the accelerometer. Real-time data accessibility was achieved through either a physical server or a cloud server Dropbox. The networking protocol for uploading to a physical server was Server Message Block (SMB), and the one for uploading to Dropbox was an application programming interface (API) named Dropbox Uploader which can be found easily on Github (Fabrizi, 2020). The system framework according to the aspect of data flow consists of 3 layers as shown in Fig. 2. The first layer is the sensor sensing the physical environment. The second layer is the single-board computer acquiring the data from the sensor and processing it. The third layer includes the local microSD card, the cloud storage Dropbox, and the server for data analysis on the backend.

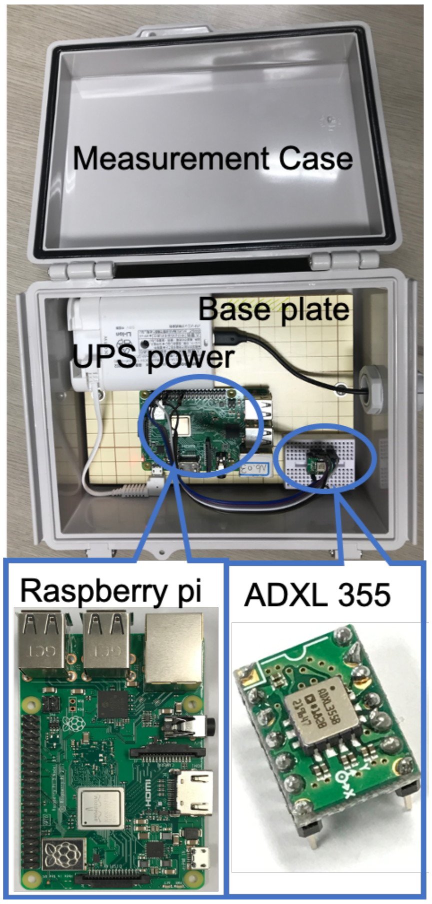


Figure 1. Prototype of IoT sensing unit

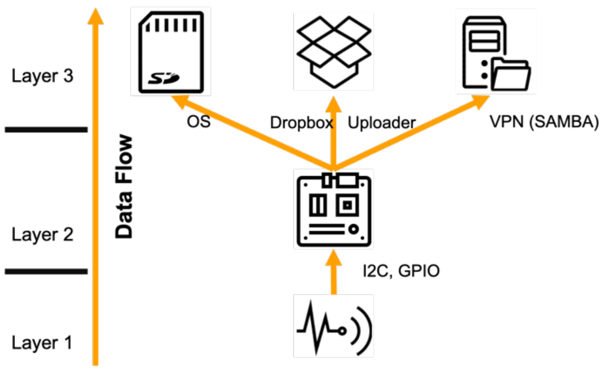


Figure 2. System framework in data flow

3. Time control

Time control consists of sampling rate and continuous monitoring. The first one is stable and sufficient sampling rate for measured data. The second one is continuous monitoring in the time domain, any interruption should be eliminated or minimized.

3.1 Sampling rate

In the measurement program, the Raspberry Pi 3 Model B+ acquires data from the ADXL355 accelerometer via I2C protocol and gives a timestamp obtained from NTP to every sample. The initial sampling method was acquiring data from the sensor consecutively without any sampling interval manipulation.

Static tests were conducted to investigate the sampling rate stability where the program was executed repeatedly by leaving the device on a desk just to measure the ambient vibration. The sampling rate shows a large variance as in Fig. 3. The variance was caused by software interrupts on the CPU, on which the sampling task could not proceed at equal intervals.

A sampling rate control method was applied to stabilize the sampling rate as shown in Fig. 4. The target sampling rate was set at 100 Hz, which is sufficient for most civil engineering structures, and the space for post-processing data can be preserved. Initially, the sample interval $\boldsymbol{t_s}$ (= $\mathbf{0.01\ s}$) was set and every sample time $\boldsymbol{t_{now}}$ was compared to the record start time $\boldsymbol{t_0}$. The operation whether to wait for a very small time or to continue was conducted according to the ratio of the time difference (between $\boldsymbol{t_{now}}$ and $\boldsymbol{t_0}$) and the sampling interval $\boldsymbol{t_s}$. Every sample file was adjusted by record end time $\boldsymbol{t_1}$. All time difference calculation referred to the initial setting $\boldsymbol{t_0}$ and $\boldsymbol{t_1}$; no accumulated sampling time error occurred in the program. The same aforementioned static tests were carried out after implementing the sampling rate control. Fig. 3 shows that the sampling rate control algorithm was effective and sampling rate stabilized at 100 Hz, the standard deviation was less than 1 Hz.

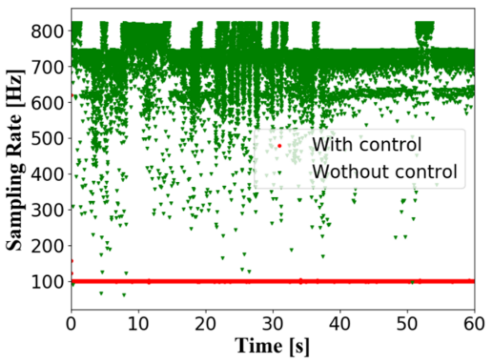


Figure 3. Performance of sampling rate in two cases

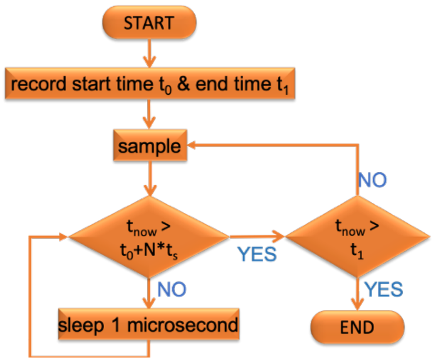


Figure 4. Sampling rate control algorithm

3.2 Real-time Monitoring

Since an earthquake event can occur any time, the time loss (defined as the time length in which the data is not recorded between two adjacent data files in the time domain), is expected to be eliminated or minimized. The problem with the previous approach (Fig. 5), which repeats the cycle of recording, writing and uploading, is that the internet connection could be unstable, so uploading procedure may not finish in time or even be interrupted. One of the possible solutions is to split the original program into two programs and run them in different CPU threads, thereby transforming the sequential process of recording, writing, and uploading to a parallel process of two parts as shown in Fig. 5. The first program is for recording and writing while the second one uploads data. These two programs are entirely separated (one will not affect or be affected by the other) and both are set as scheduled tasks. The program in charge of recording and writing automatically runs when the device boots and the program dealing with uploading will run as schedule task at a certain time interval.

Another issue is the write method that causes time loss in continuous monitoring. The time loss is positively correlated to the setting record time due to writing all data to a file at once. One simple test for verifying the relation between the time loss and the setting record time was carried out. Following the initial method, record time was set to repeat 10 times from 10s to 300s with an interval of 10s. As can be seen in Fig. 6, the time loss increases with the increase in the record time; the writing process becomes time consuming when the file size increases.

The solution is to spread the writing task into every sampling time where sleep time can be utilized reasonably. A test with same test setting as done in the initial writing method was carried out to verify the effectiveness of the improved method. The test results are shown in Fig. 6, the time loss is reasonable and ignorable.

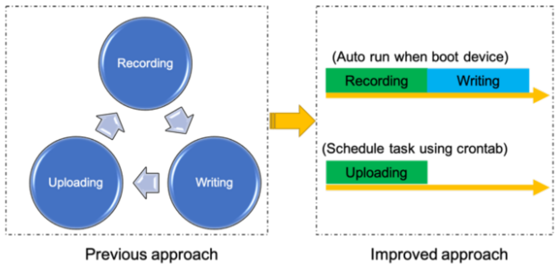


Figure 5. Solution of packet loss and time loss

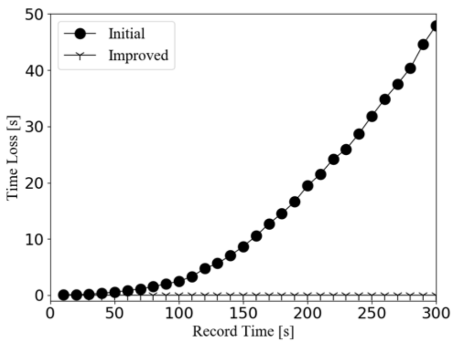


Figure 6. Time loss in two cases

4. Accuracy verification via shaking table tests

The uni-directional shaking table tests were carried out to investigate the performance of the proposed system under different frequencies and amplitudes. The reference sensor used in this study is a high-quality servo velocity seismometer VSE-15-D. A uniaxial shake table (APS-113) was used to simulate sinusoidal motion with different frequencies and amplitudes. The sinusoidal signal was generated by WF-1974 function generator (NF Corporation, 2013) with different frequencies and then amplified by SVA-ST-30 power amplifier (San-Esu Co,Ltd., 2015). The layout of specimens on the shaking table is shown in Fig. 7.

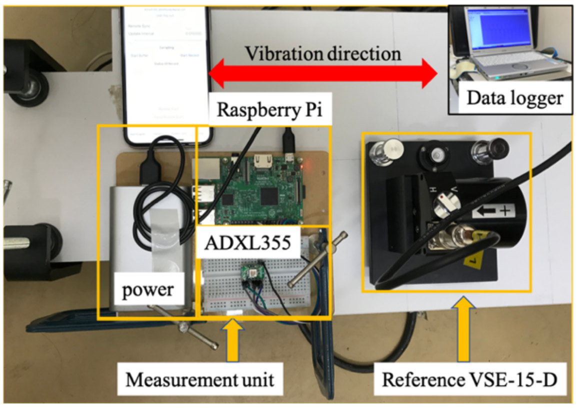


Figure 7. Setting layout of the shaking table tests

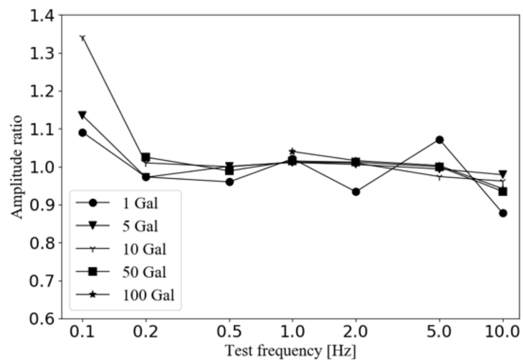
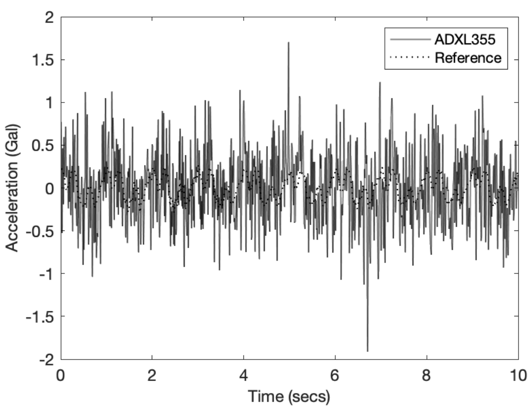
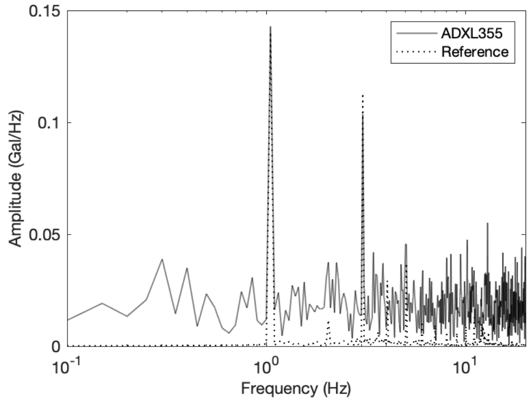


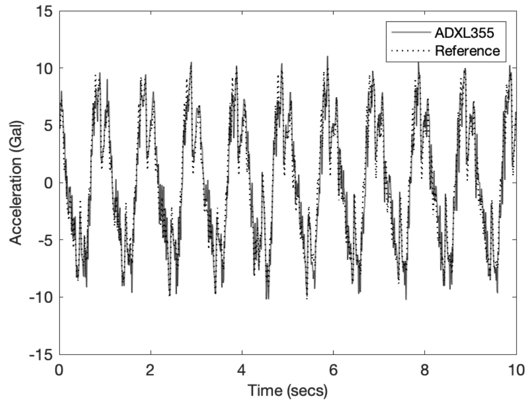
Figure 8. Results of the shaking table tests



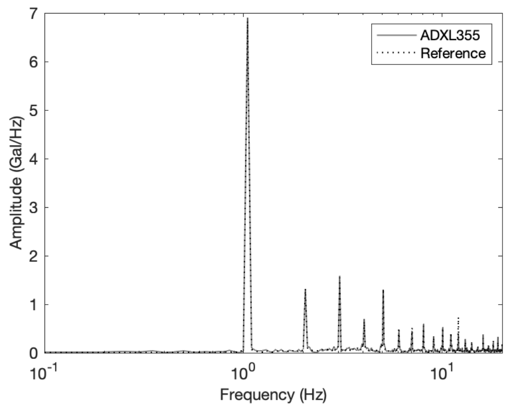
(a) Waveform at f = 1.0 Hz, Acc=1 Gal



(b) Fourier spectrum at f = 1.0 Hz, Acc=1 Gal



(c) Waveform at f = 1.0 Hz, Acc=10 Gal



(d) Fourier spectrum at f = 1.0 Hz, Acc=10 Gal

Figure 9. Comparison of records with the reference sensor

Table 1. Case setting of the shaking table tests

Freq. / Amp.	0.1 Hz	0.2 Hz	0.5 Hz	1.0 Hz	2.0 Hz	5.0 Hz	10 Hz
1 Gal	◎	◎	◎	◎	◎	◎	◎
5 Gal	◎	◎	◎	◎	◎	◎	◎
10 Gal	◎	◎	◎	◎	◎	◎	◎
50 Gal	×	◎	◎	◎	◎	◎	◎
100 Gal	×	×	×	◎	◎	◎	◎

To investigate the capability of the ADXL355 accelerometer to capture structural seismic response vibration, sinusoidal excitation with frequencies from 0.1 to 10.0 Hz and amplitudes from 1 to 100 Gal were implemented, as shown in Table 1. For every case in the tests, the time taken for measurement was assured so that there were enough cycles of sinusoidal waves. The sinusoidal motion recorded by the ADXL355 accelerometer and that recorded by the reference sensor were compared in terms of time and frequency domains of acceleration time history records. Peak amplitudes by Fourier transform of the ADXL355 accelerometer and the reference sensor in the same test case were compared. The amplitude ratio, which is the amplitude of the ADXL355 divided by that of the reference, is shown in Fig. 8. It can be seen that the amplitude ratio is relatively stable and coincide with the reference in the frequency range between 0.2 Hz and 10 Hz with all amplitude cases except for the small amplitude 1 Gal. The variance of performance in low amplitude is due to the effect of noise coming from the MEMS sensor.

Two example cases (f = 1.0 Hz, Acc =1 Gal & f = 1.0 Hz, Acc = 10 Gal) of the comparison between the ADXL355 accelerometer and the reference sensor in both time domain and frequency are presented in Fig. 9. As can be seen in Fig. 9-a, the vibration signal is covered by noise which is about 1 Gal, and Fig. 9-b shows that the noise is randomly distributed in both high and low frequencies. Nevertheless, the measurements from the IoT sensor basically agree well with the results from the reference sensor. Although the waveforms acquired from the IoT sensor does not precisely overlap with the ones from the reference sensor, the primary frequency can be clearly captured and reflected by the IoT sensor.

5. Application of SSM system

The prototype of SSM system (see Fig. 1) was installed on the 8th floor of a 10-storey reinforced-concrete-frame building in Saitama University for a long-term seismic events monitoring in 2019 June, as shown in Fig. 10. Four earthquakes listed below were observed from the deployed prototype during the 4-month deployment period, though the seismic intensity in the region where the prototype was deployed was low in JMA seismic intensity scale.

1) M6.7 Yamagata Offshore (2019/06/18)
2) M5.5 Chiba Prefecture (2019/06/24)
3) M6.6 Mie Offshore (2019/07/28)
4) M6.4 Fukushima Prefecture (2019/08/04)

The records from the nearest observation station (K-NET SIT010) of strong-motion seismograph networks in Japan (K-NET and KiK-net) were collected for the comparison with that of the proposed system. The distance between two observation locations is approximately 13 km. The orthogonal tri-axis measurement direction was aligned to East-West (EW), North-South (NS) and Up-Down (UD) direction, the same as the observation station record.

Measured acceleration waveforms from both the IoT sensor and the reference in the M5.5 Chiba Earthquake for 3 axes are shown in Fig. 11. The data was extracted from continuous monitoring according to the record time from the observation station and then compared with the reference. The abnormality can be easily observed in the waveforms when an earthquake happens. The measured waveforms can represent the structural seismic response roughly, though the accurate waveform data concerning earthquakes with amplitude smaller than 2 Gal is basically hidden due to the ambient signal as in Fig. 11.

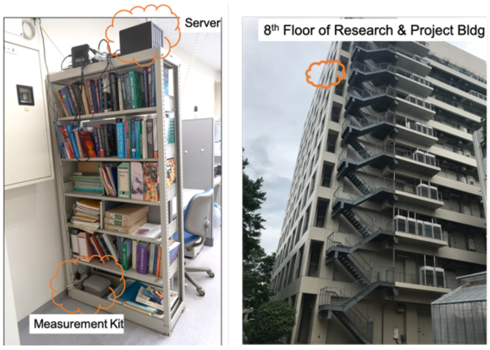
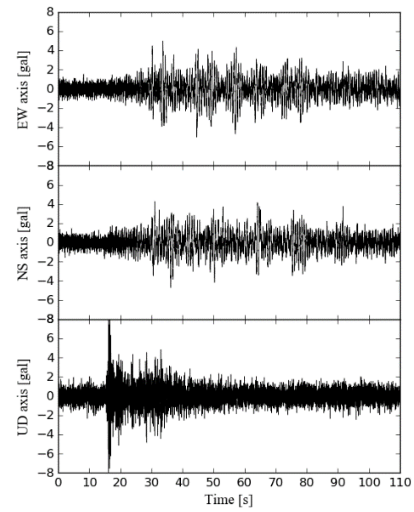
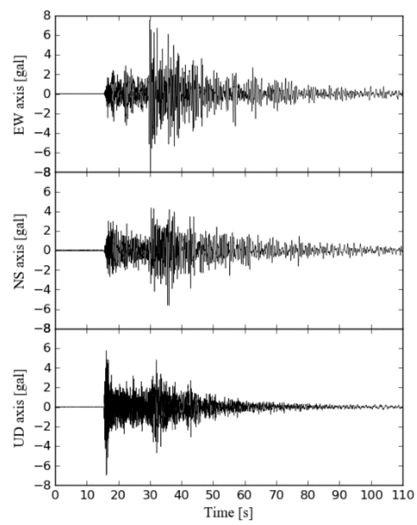


Figure 10. Deployment of SSM system

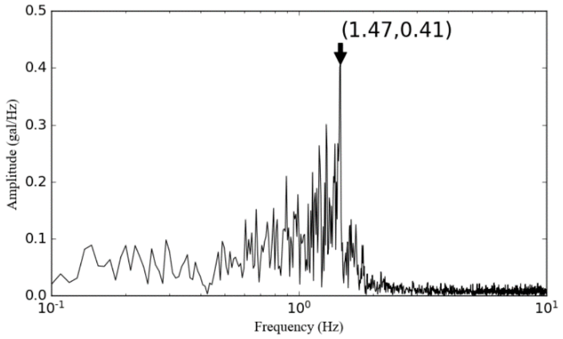


(a) Waveform measured by IoT sensor

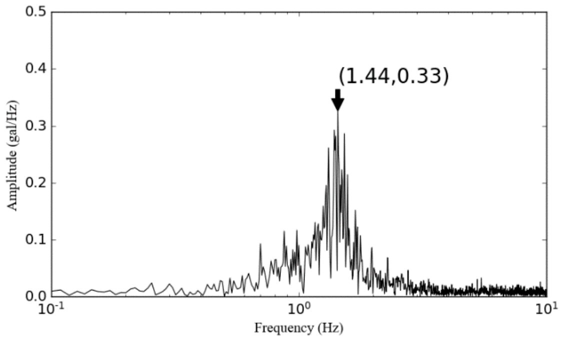


(b) Waveform measured by K-NET SIT010

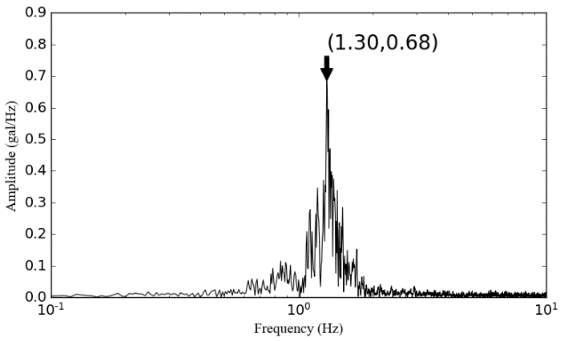
Figure 11. Waveform comparison for IoT and reference



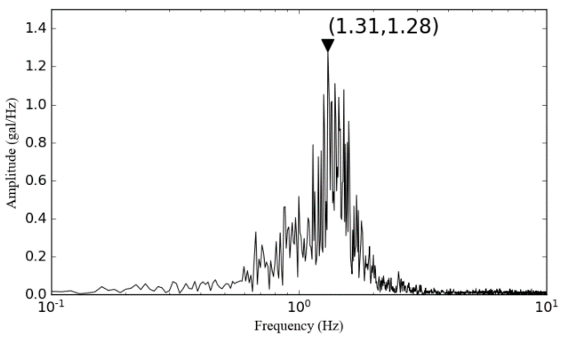
(a) Fourier spectrum in M6.7 Yamagata



(b) Fourier spectrum in M5.5 Chiba



(c) Fourier spectrum in M6.6 Mie



(d) Fourier spectrum in M6.4 Fukushima

Figure 12. Fourier spectrums of the measured vibration

Fourier spectrums of observed vibration along EW direction by the IoT sensor for 4 earthquakes are shown in Fig. 12. The dominant frequency of the structure at the prototype-deployment location is identified around 1.4 Hz. Only noise can be observed under 2 Gal in the UD direction, showing the limitation of the accuracy of the proposed system. Nevertheless, the proposed system can observe the earthquake at locations where the seismic intensity is as low as 1 in JMA scale. With advancements in the resolution and sensitivity of MEMS accelerometer in the future, the proposed system can be expected to show better performance in structural seismic monitoring.

6. Conclusion

This paper proposed a low-cost, real-time, and long-term IoT sensing-based SSM system which is feasible to be deployed densely. Integrated with the function of data acquisition, data storage, and data transfer, IoT devices considerably reduce the cost of SSM with reasonable performance and accuracy. The effectiveness of the proposed system has been verified via shaking table tests and long-term seismic response monitoring of structures. Through all experiments above, this proposed SSM system can carry out 24/7 monitoring with stable sampling rate at 100 Hz and with 2-Gal detectable acceleration level. The proposed prototype is capable to monitor the structural seismic response under moderate earthquakes.

References

Allen Richard M., Brown Holly, Hellweg Margaret, Khainovski Oleg, Lombard Peter, and Neuhauser Douglas 2009. Real-time earthquake detection and hazard assessment by ElarmS across California. GEOPHYSICAL RESEARCH LETTERS. VOL. 36, L00B08, doi:10.1029/2008GL036766

Andrea Fabrizi, 2020. Dropbox Uploader, viewed 11 May 2020. <https://github.com/andreafabrizi/Dropbox-Uploader>

García Jorge Ruiz 2012. Mainshock-Aftershock Ground Motion Features and Their Influence in Building's Seismic Response. Journal of Earthquake Engineering. 16:5, 719-737

NF Corperation, 2013. Signal generator, viewed 11 May 2020. <http://www.nfcorp.co.jp/english/pro/mi/sig/f_gen/wave/index.html>

Padgett Jamie E., and Desroches Reginald 2007. Bridge Functionality Relationships for Improved Seismic Risk Assessment of Transportation Networks. Earthquake Spectra. February 2007, Vol. 23, No. 1, pp. 115-130

San-Esu Co,Ltd., 2015. SVA series, viewed 11 May, 2020. <http://www.san-esu.com/product030.html>

Thomson Douglas J. 2013. The economic case for service life extension of structures using structural health monitoring based on the delayed cost of borrowing. J Civil Struct Health Monit. (2013) 3:335–340 DOI 10.1007/s13349-013-0057-0

Tokyo Sokushin, 2010. Servo Velocity-meter VSE-15D, viewed 11 May 2020. <http://www.to-soku.co.jp/en/products/servo/pdf/vse15d_e.pdf>

Veras José Holguín, Taniguchi Eiichi, Jaller Miguel, Vera Felipe Aros, Ferreira Frederico, and Thompson Russell G. 2014. The Tohoku disasters: Chief lessons concerning the post disaster humanitarian logistics response and policy implications. Transportation Research Part A. 69 (2014) 86–104