第20回性能に基づく橋梁等の耐震設計に関する
シンポジウム講演論文集（2017年7月）

Seismic Response and Health Monitoring System for Takamatsu Bridge using Smart Devices

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1. INTRODUCTION

The Infrastructure Health Report issued by Japan Society of Civil Engineers gave Japan's bridge infrastructure an overall D in 2016 [1]. Reports from the National Highway Maintainance Budget (2005) indicates that a total of £1.44 billion is needed to rehabilitiate existing road and bridges infrastructure system [2]. National budget priorities do not allow for this high level of investment, so many existing infrastructure systems will be left deficient. Determining prioritization of the maintenance, repair, and replacement of this infrastructure requires inspection, a process that can be costly and prone to error. In case of large-scale infrastructure systems such as bridges, diverse dynamic loads, including traffic, wind and earthquakes can aggravate the condition of the structures. Structure Health Monitoring (SHM) can provide a useful diagonistics tool for ensuring integrity and safety, detecting damage and evaluating performance deterioration of civil infrastructures [3-5].

After the historic 2011 Great East Japan Earthquake and a more recent 2016 Kumamoto Earthquake, bridge seismic response monitoring has been realized as one of the most important issues for earthquake resilience of urban areas. Though, numerical simulation of both structural seismic response analysis and ground motion simulation are being conducted for bridges, it is very difficult to predict the behavior of both ground shake and structural response due to lack of instrument measured data. Without such a record, neither damage and behavior of structures during strong earthquakes can be compared to the seismic design criteria nor proper decisions concerning rational repair and reconstruction could be made. The Micro Electro Mechanical System (MEMS) based measurement has been applied to SHM systems for bridge, such as wireless sensor (Spencer et al. 2004) [6], or dense earthquake and SHM system such as Community Seismic Network (CSN) (Clayton et al. 2015) [7]. However, in general, these traditional measurement system, that combines accelerometers, data log, hard disk, computer, power supply, modem and network connection, is often high cost and difficult for wide application in structures.

Meanwhile, having significant computational power, large memory resources, built-in batteries, processor units, and a variety of MEMS, modern smart devices can offer a promising hardware and software environment that can be used as SHM components. Smart devices, with their on-board computational and communication capabilities, improvements in built-in sensors and easy to offline or online programmable functionality, simplifies the collection of information about existing infrastructures and thus offer new opportunities in the field of seismic and structural response measurement with extremely low initial and maintenance cost. Several researchers (Yu et al

2012 [8], Dashti et al 2011 [9], Morgenthal and Hopfner 2012 [10,11], Naito et al. 2013 [12], Reilly et al 2013 [13], Feng et al 2015 [14], Han et al 2014 [15], Shrestha et al 2015 [16]), studied the measurement and monitoring ability of smart devices through laboratory and field tests and confirmed the potential usage of smart devices in the health monitoring of civil infrastructures. However, the performance of Smart devices as structural measurement and monitoring device has not been verified before its practice in real structural monitoring or seismic response recording. Also, reliability of using smart devices for long-term monitoring with stable and easy data transport has not yet been clarified.

This study investigates the implementation feasibility of long-term bridge health monitoring technique using smart devices. In this study, a real field application test of the measurement system applied to long-term seismic-response and environment-vibration measurement of the Takamatsu bridge has been carried out using smart devices and cloud server. Unlike traditional network based data acquisition server, modern cloud based server used in this study, enable to compose a low cost smart sensor network for easy data upload and access. With all these features, this study sets a decentralized and self-governing smart device based SHM framework which can even be pertained by very limited equipment and labor resources. First, a measurement system including a group of smart devices has been established successfully. The system is then connected to cloud server for real-time data acquisition. The feasibility of the system for long term monitoring has been evaluated based on stable and continuous measurement and data transfer. A few seismic acceleration response records of Takamatsu bridge were captured for the observable acceleration level of over 5 gal. These field measurement results show that the dynamic properties extracted from smart-device-based system is very similar to those of high-quality-sensor-based system.

2. TAKAMATSU BRIDGE: AN OVERVIEW

The Takamatsu bridge, as shown in Figure 1 was built in 1982 at Miyazaki, Japan. It is a PC box continued girder bridge with 7 spans, 444 m in length and a pile basement. The bridge has BP bearing at abutments and pin bearing at the pier part and with a Gilber hinge at 3rd and 5th span. This bridge connects two parts of the city separated by Oyodo-Gawa river and maintaining the transportation function as a key for resilience of this area. Instrumentation of this bridge offers opportunities to study and understand dynamic and long-term behaviours. It will be of great interest to monitor and evaluate the long-term structural performance of such bridges under not only seismic but also service loads. Especially, long term seismic monitoring can be a useful way to check its functionality and damage of risk under eathquakes.

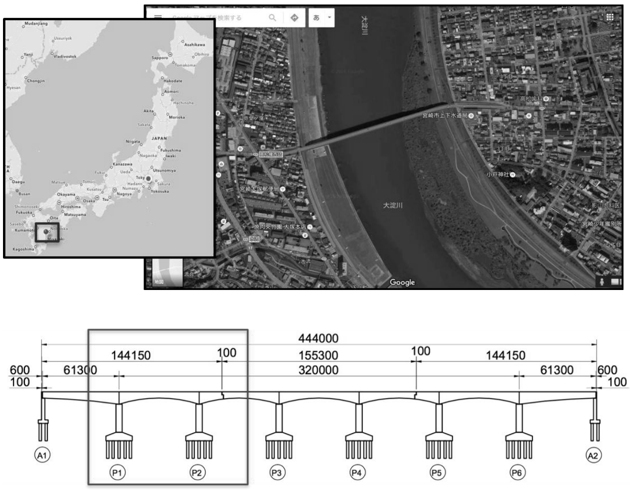


Figure 1. Longitudional section of Takamatsu bridge, Miyazaki

3. MEASUREMENT APPLICATION DEVELOPMENT FOR SMART DEVICES

(1) Application Development Environment

Measurement Application program for smart devices was developed, which interacts with hardware and operating-system features to make the built-in MEMS sensor components available and are responsible for acquiring data, analyzing data, storing data, and transfering useful data to the cloud. First of all, the operating system builds the required interconnecting infrastructure network platform to communicate and process the information required for services and monitoring applications. Then Apps, also known as the software applications for smart devices, performs these specific tasks, as mentioned above and as shown in Figure 2. In this study, the app was developed based on the Objective-C programming language in the integrated development environment Xcode. Dropbox sync API (Dropbox developer, 2014 [17]) is used as data-restoring cloud server. Using this API, the app can read, create, and modify files. It also notifies app when the parameter-setting file in the cloud server is changed by other terminals, such that the app can respond instantly and synchronize its measurement settings to the newest command.

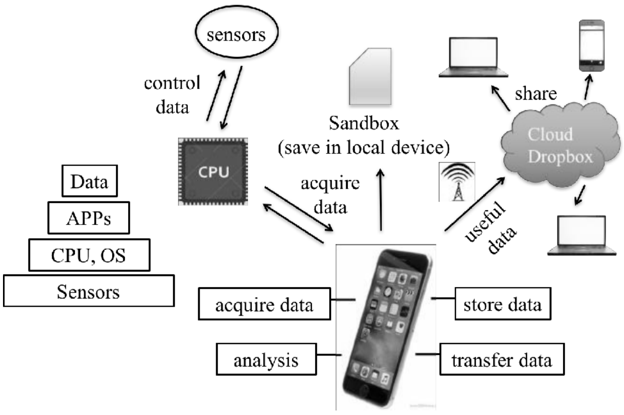


Figure 2. Overview of App Development using Smart Devices

(2) Measurement System Development - Methodology

The developed measurement application program is, primarily, a background-executing program that runs in iOS devices and performs 24 hours of continuous acceleration measurement. Measurement record are initiated manually by pressing the record button in the User Interface of the application program. Similarly, when the user press the stop button, recording is complete and the record file is uploaded to cloud server.

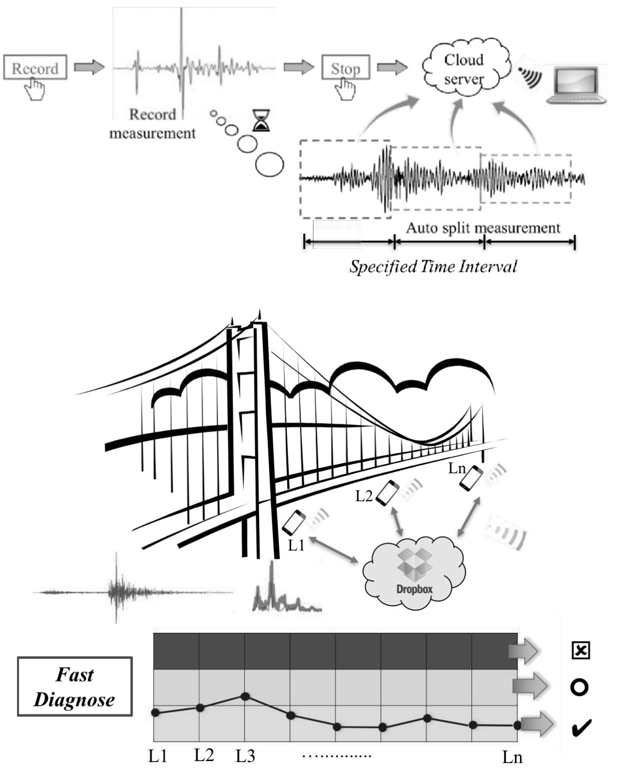


Figure 3. Measurement System Overview using Smart Devices

However, since 24 hours of continuous measurement (i.e. long-term measurement) is taken in this study, record data during measurement is subdivided into multiple record files, and uploaded independently. This ensures that the probability of unoccasional crashing of program due to allocation of large amount of memory resources in processing a single large data file is nullified, thus making the system stable and data transport smooth.

Smart devices being all-in-one multifunctional device that combines sensor, data log, on-board computation and intelligence, data process, storage and transfer; and with a network of interconnecting communication interface a complete measurement and monitoring system has been developed. As depicted in Figure 3, this measurement system consisting of independent smart device can be installed at different locations of a bridge and measure data independently. Moreover, when all the devices are connected to a common network with the ability to communicate with each other, then a robust measurement system for whole bridge can be established. In this way, real-time record data from all the terminals can be obtained. Also, with real-time processing of the record data via the computational capability of smart devices, faster diagose of the structure can be generated in the form of damage index report or emergency warning alarm output, especially during the case of earthquakes.

4. LONG-TERM FIELD MEASUREMENT AND VALIDATION TEST

(1) Overview of Field Measurement

A field experiment is conducted to verify the proposed method. More specifically, the purpose is to verify whether the proposed method can leverage commercially available smart devices to characterize the structural vibrations at wider frequency ranges and use these measurements for identifying the health status of structure. For this purpose, Takamatsu bridge as described in section 2 is selected. To measure accuracy, the identified system from smart devices will be compared with the high precision accelerometer sensor results as a reference solution.

To measure the dynamic response of the bridge model, the bridge has been instrumented with four smart devices (iPhone 5s labelled as 1, 1a, 2 and 3) inside of the box girder at three different locations, two directly over the pier, one at the 1/4th span between two piers and one at the midway between the two piers as shown in Figure 4.

High precision seismometer sensors (Hakusan Industrial SU501) [18] at the respective locations had already been installed after the 2016 Kumamoto earthquake, thus giving measurements from both the smart devices and high precision sensors. The smart devices are fixed via double-sided adhesive tape. Data is transmitted wirelessly to the cloud server by setting up wifi connection via router to each smart device terminals. Power supply and internet connection was established by mobilizing already installed power source and LAN service inside of the box girder. The reference coordinate of smart devices for measuring vibration response is shown in Figure 4. Table 1. summarizes the basic properties of smart device and high precision accelerometer sensor used in the field measurement.

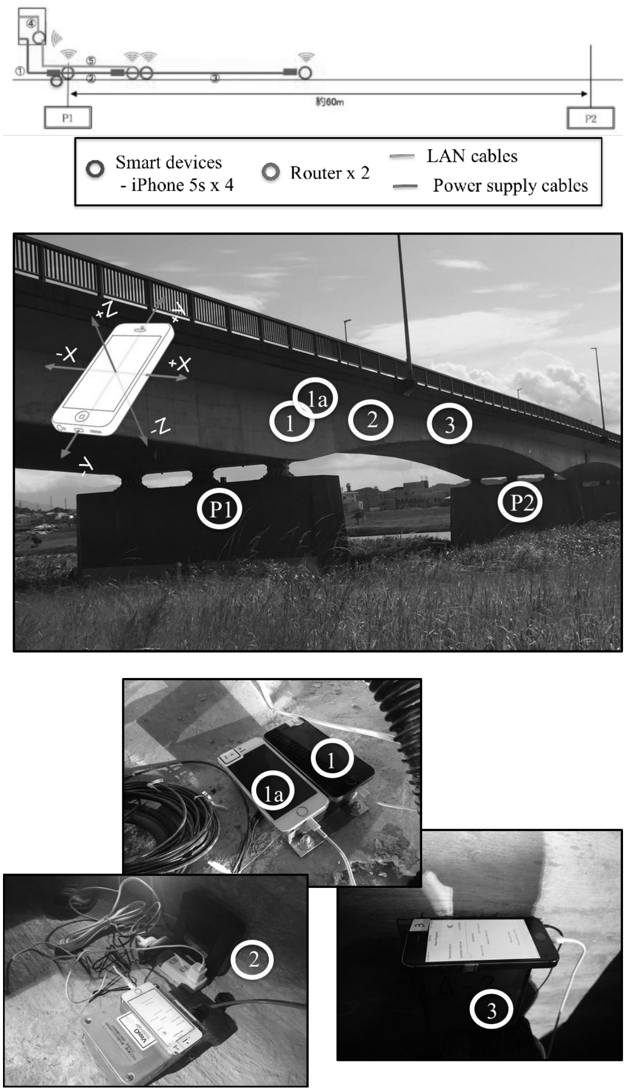


Figure 4. Installation of smart devices on Takamatsu bridge

(2) Sensor system and specifications

The reference-measurement systems, as shown in Figure 4, consists of three high-quality servo-acceleration sensor and four other widely used smart devices (iPhone 5s) embedded with MEMS accelerometers. The MEMS accelerometers inside of smart devices can sample stably at a maximum frequency of 100 Hz (corresponding to a Nyquist frequency of 50 Hz). This sampling frequency is generally considered sufficient for most engineering applications, including ground-shaking or structural-response measurement.

Table 1. Reference sensor and smart device properties

Property	SU501 	iPhone 5s 
Sensor Maker	Hakusan Corporation	Bosch Sensortech
Sensor Model	SU501	BMA220
Sensor Type	Servo acceleration Sensor	MEMS
Sensitivity	----	15.6 mg
Resolution	0.0006 gal	6 bit
Acceleration Range	±4g	±2g/±4g/ ±8g/±16g

(3) Sampling frequency deviation and error correction

Figure 5. shows the example record of the sampling rate for iPhone 5s set to 100 Hz.

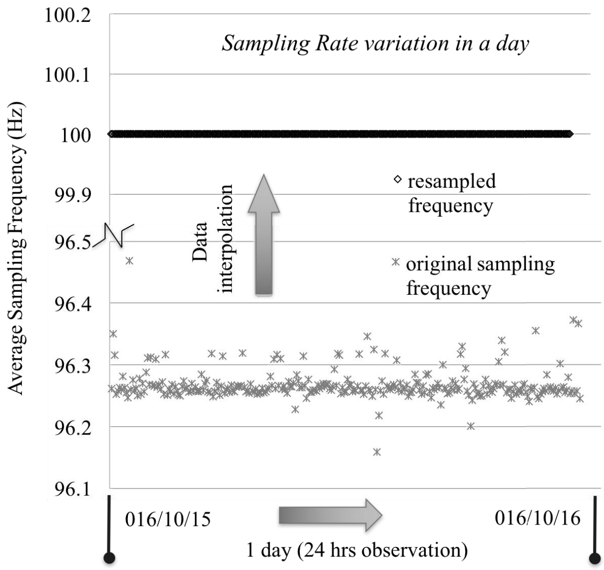


Figure 5. Variation in sampling frequency offered by iPhone 5s

Over the entire measurement, the sampling frequency measured by iPhone 5s at location 1 is observed to be around 96.25 Hz. However, little inconsistencies are observed, as sometimes the actual sampling rate goes higher while sometimes it goes lower than the observed frequency. This may be due to the consequence of multitasking system that signal output data are not sampled at exactly equal intervals. This error in sampling frequency is random and the randomness is different in different smart devices.

However, there are several numerical methods, such as data resampling or use of the real sampling time, to correct this error. In this study, data resampling to a common target rate of 100 Hz is performed by interpolating from the raw data. Unification to a common target rate, as a pre-processing step, ensures that all interpolated samples in each data window will be equidistantly separated in time.

(4) Long-term monitoring record overview

After installation, 24 hours continuous measurement from all smart devices are being performed and recorded data can be monitored in real-time. Since the start of measurement i.e. from 7^{th} month of last year, recordings of two smart devices at location 1 (iPhone 5s_01 and iPhone 5s_1a) were interrupted due to power issues.

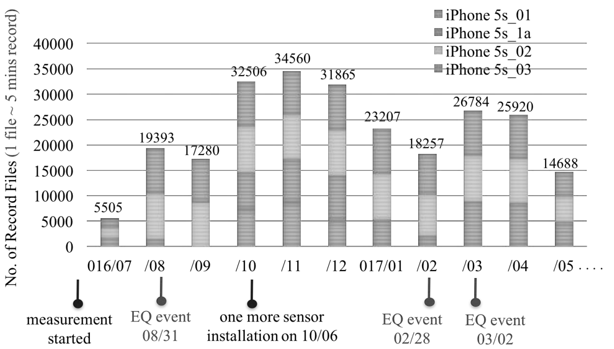


Figure 6. Data volume chart for long-term(24 hrs) measurement

However, we can observe a continuous, non-interrupted measurement from two other smart devices at location 2 and 3 (iPhone 5s_02 and iPhone 5s_03) as depicted in data volume information chart in Figure 6. This continuous and stable data measurement justifies the applicability of smart devices for long-term vibration monitoring applications.

(5) Earthquake Response Observation at the bridge

With 24 hours of continuous environment-vibration measurement, the smart devices recorded 3 earthquake events from the date of installation. The epicenter, distribution of Peak Ground Acceleration (PGA) and other important details of those 3 earthquakes are shown in Figure 7 and listed in Table 2.

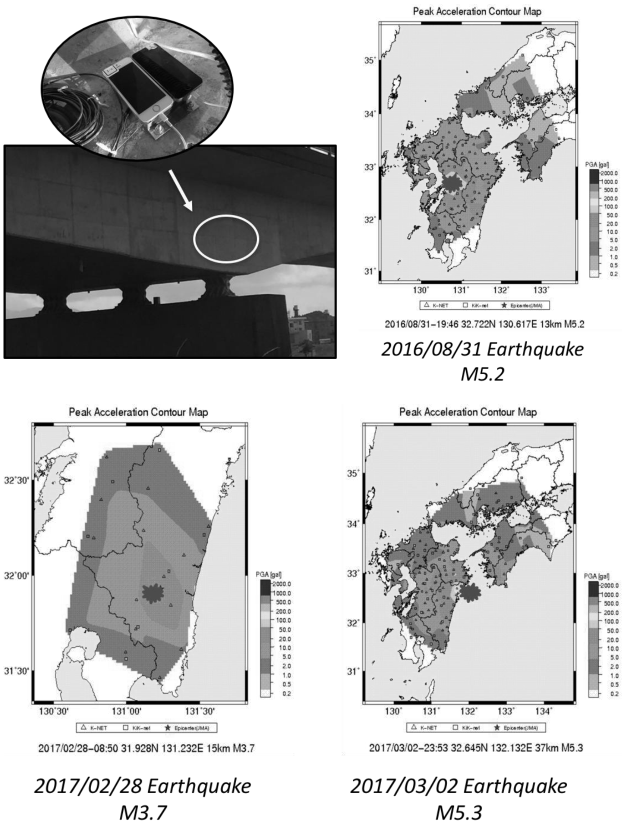
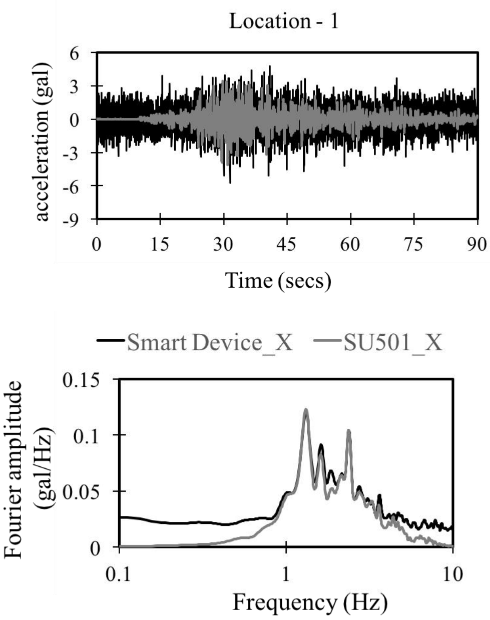


Figure 7. Epicenter of 3 different recorded earthquakes (K-NET & KiK-net NIED)

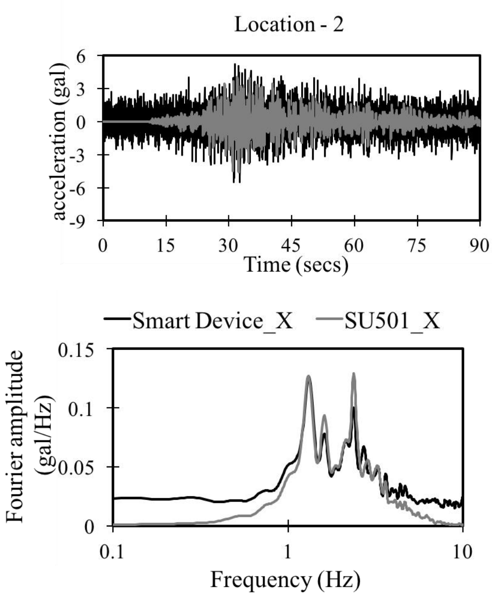
Table 2. Detail of 3 different earthquakes recorded at bridge

Details	Earthquake 1	Earthquake 2	Earthquake 3
Origin Time (JST)	8/31/2016 19:46	2/28/2017 08:50	3/2/2017 23:53
Epicenter	Kumamoto, Miyazaki	Miyazaki	Miyazaki
Latitude	32.72N	31.93N	32.65N
Longitude	130.62E	131.23E	132.13E
Depth (km)	13	15	37
Magnitude	5.2	3.7	5.3

From the peak acceleration contour map it can be seen that the average PGA near the bridge location is around 10 gal which means that all the 3 earthquakes recorded in this location were small in amplitude. Among the 3 recorded earthquake events, acceleration waveform along bridge axis for 017/03/02 earthquake at 3 different locations is shown in Figure 8. Acceleration records of the servo-acceleration sensors were taken for the purpose of comparing the waveforms and Fourier spectrum of the simultaneous records with the record of smart devices. Because the measurement of reference sensors system and the smart devices system were made independently, time lag between the records of these two systems exists. The time lag was firstly extracted from the shift time of the peak of cross-correlation waves. Then the whole waveform was moved forward or back with the time length of the extracted time lag. The comparison between acceleration waveforms recorded by the reference system and the smart device system are shown in Figure 8.



(a)



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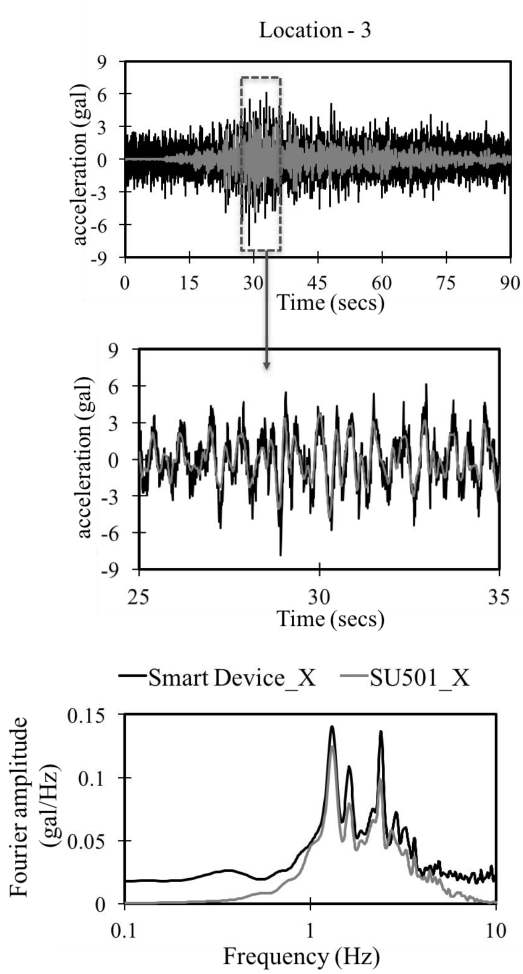

(c)

Figure 8. Time History and Frequency Domain comparison for 017/03/02 Earthquake at 3 different location of bridge

Since noise components of approximately ± 5 gal are the continuous signal obtained from the MEMS sensors, accurate waveform data concerning earthquakes with smaller magnitudes are hidden by noise components as seen in the record of all 3 earthquakes. Nevertheless, some significant continuous peaks can be observed that distinguish the characteristics of an earthquake. Though it is difficult to compare the waveforms of these two systems in time domain due to high noise level, it can be seen that acceleration measurements from smart device showed high agreement with that of reference system as depicted in Figure 8(c). Similarly, the Fast Fourier Transform (FFT) which is one of the commonly used technique to identify dynamic properties of structures in the frequency domain was applied. The fundamental natural frequency of the bridge is identied by the peak picking method i.e. by selecting the frequency corresponding to the first peak. As can be seen from comparison figures, the measurements of smart device

Table 3. Dynamic properties comparison between smart device and Hakusan sensor measurement along bridge longitudinal direction

Location	Earthquake recorded date	016/08/31		017/02/28		017/03/02	
		freq (Hz)	amp (gal/Hz)	freq (Hz)	amp (gal/Hz)	freq (Hz)	amp (gal/Hz)
Location 1	Smart device	-	-	3.765	0.107	1.311	0.12
	Hakusan	-	-	3.732	0.100	1.311	0.123
	% Error	**-**	**-**	**0.884**	**7**	**0**	**2.44**
Location 2	Smart device	1.467	0.127	2.774	0.070	1.311	0.126
	Hakusan	1.467	0.119	2.762	0.060	1.311	0.127
	% Error	**0**	**6.722**	**0.434**	**16.667**	**0**	**0.787**
Location 3	Smart device	1.467	0.116	2.733	0.067	1.311	0.140
	Hakusan	1.467	0.104	2.749	0.060	1.311	0.125
	% Error	**0**	**11.538**	**0.582**	**11.667**	**0**	**12**

agree well with the measurements of reference accelerometers in terms of frequency identification with a maximum error of 0.88%. However, Fourier amplitude comparision between the two shows greater discrepancy with a maximum error of around 16%. This error is smaller for larger magnitude earthquakes and larger for smaller magnitude earthquakes, since for smaller earthquakes, waveform data are hidden by noise components as mentioned above. The identified natural frequencies and Fourier amplitude measurements of bridge during different earthquakes and at different locations are summarized in Table 3. These results justifies the reliability of using smart devices for real field applications. Moreover, for further analytical purposes in the future, the system shall also be tested to see if it can produce valuable modal-identification results for SHM.

5. REAL TIME DATA VISUALIZATION SYSTEM USING SMART DEVICE

Data visualization is essential to give meaning to raw data. Therefore, real-time recorded data visualization function within the measurement application program has also been developed for fast and resilient monitoring of structures (bridges, buildings). Such system will monitor for post earthquake safety and evaluate for the early detection and resolution of the damaged area. In this study, data recorded from all the devices connected to the same dropbox account can be visualized in terms of acceleration time history plot, Fourier Spectrum plot and Rotation time history plot. Apart from the recorded data it is also possible to observe record parameters and status of devices (battery, memory, etc.) that are under long term measurement. The application also uses the built-in GPS sensor and tracks the location of record that can be visualized in form of location map. Figure 9. shows the different forms of recorded data visualization using the developed measurement program in smart devices.

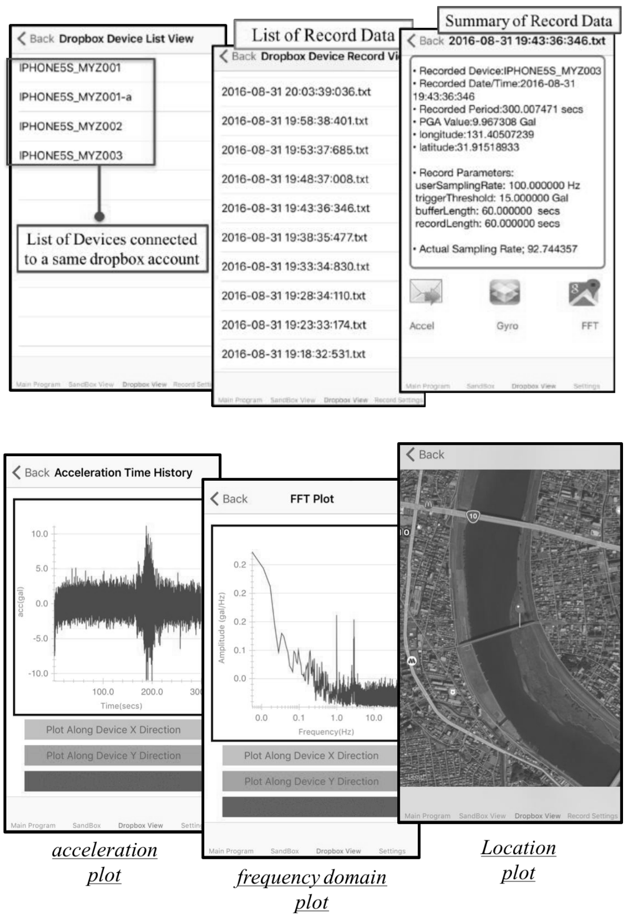

Figure 9. Graphical visualization of recorded data using the developed measurement program in smart devices

6. CONCLUSION

This paper presented the implementation feasibility of long-term bridge health monitoring technique using smart devices. Different from the state-of-the-art conventional SHM methods that requires expensive sensors and data acquisition components, the proposed method enables the dynamic characteristics of structures to be derived with consumer-grade devices without the need of intensive instrumentation. To validate the proposed method, response of Takamatsu bridge during some of the recorded earthquakes using smart devices together was compared with the reference accelerometer. Results show that proposed method has potential to identify the natural frequency with reasonable levels of accuracy.

This study thus emphasizes greater potential of smart devices for civil infrastructure monitoring and health assessment in a rapid, remote, automated, and quantified framework. Robust implementation in smart device-based SHM can radically influence the future advancements in smart, sustainable, and resilient infrastructures.

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