Automated Real-time Seismic Monitoring System for Bridge and Building Structures

橋梁および建築構造物のリアルタイム地震モニタリングシステム

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地震などをリアルタイムに検知し，損傷等による構造物の異常を検知する自動的なモニタリングシステムを開発した。本システムは，無線加速度計ネットワークにより，構造物の固有振動数・振動モード形状・傾斜角度などの構造物の特性の変化を監視する。独自のアルゴリズムにより振動特性を高精度に推定し，リアルタイムに異常を検知する。高速道路の橋梁の 2 件の実測データにより，本システムの妥当性および異常検知手法の有効性を評価した。舗装工事による橋梁重量の小さな変化を固有振動数の微小な変化として検出できたことから，軽微な損傷や構造の劣化などの構造物の変状による微小な剛性変化も同様に検出可能といえる。さらに，地震をリアルタイムに検知し，地震直後の構造物の即時性能評価に適用可能である。
キーワード：モニタリング，損傷検知，傾斜角度，固有振動数，常時微動
This paper presents an automated real-time monitoring system that is able to identify seismic events like earthquakes and to detect anomalies in the structures after these events using wireless accelerometer networks. Natural frequencies, modal shapes, and geometry inclination are indicators for evaluating structures. An original algorithm was developed to identify modal parameters effectively and detect anomaly in real-time. The application in two highway bridges confirmed the value of the wireless monitoring system. The detection of such small changes in bridge weight due to road surface construction work confirmed the ability to detect slight damage or deterioration in structure. In addition, the result confirmed that real-time detection of earthquakes and real-time evaluation of the structural performance is possible to implement.
Key Words: Monitoring, Damage detection, Inclination, Natural frequency, Ambient vibration

1. INTRODUCTION

An automated monitoring system of bridges is currently highly interested in Japan to enable early evaluation of structures safety due to earthquakes and deterioration. Various monitoring approaches including vibration-based method [1), 2), 3)], vision-based method [4)], or optical fiber strain method, have been investigating for recent decades to monitor structures. Getting cheaper in data acquisition and hardware cost, vibration-based monitoring, especially integrated with wireless sensing networks, becomes more common for evaluating the performance of structures in real-time. There are several remarkable examples of monitoring systems on existing structures such as the system of the Jindo Bridge in Korea [5), 6)], the Humber Bridge in England [7)], the Akashi-Kaikyou Bridge in Japan [8), 9)], the Tamar Bridge in England [10)] showing the value of vibration-based monitoring system using wireless sensor networks.

Damage or anomaly detection is one of the key functions in any monitoring system. The vibration-based monitoring approach is based on the principle that an abnormal vibration characteristic will be generated due to structural changes as cracks, deterioration, or damages. The natural frequencies and modal shapes are functions of structural weight and stiffness; hence, a reduction in natural frequency may indicate a stiffness reduction due to damage, cracks, or mass

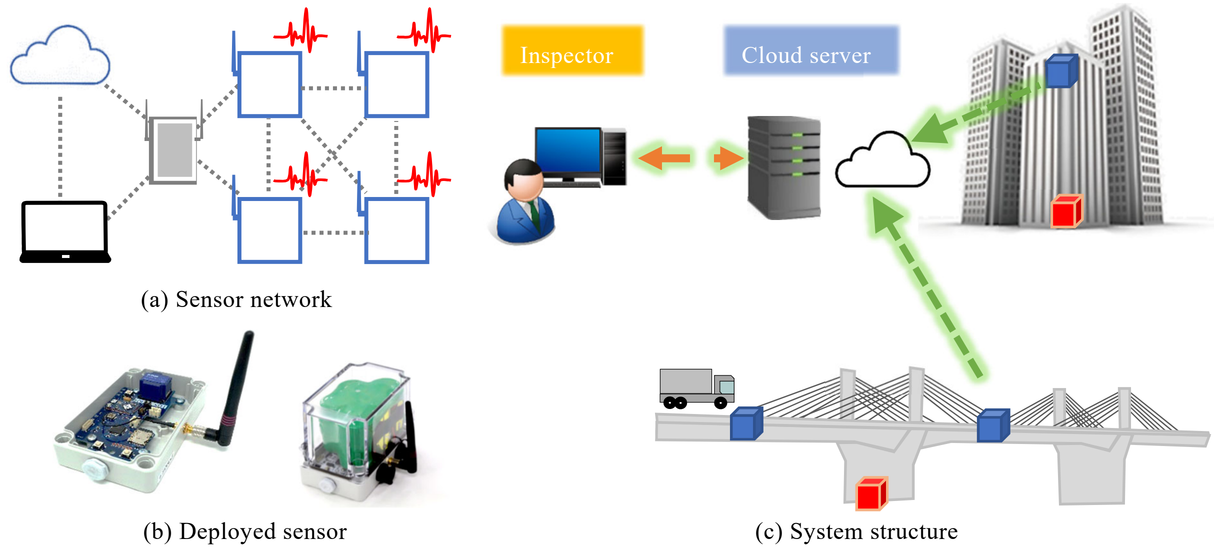


Fig. 1. Concept of wireless sensor network monitoring

change in structures. However, due to environmental factors like the temperature, the modal properties change as well, making the detection of small variations more difficult.

In this paper, an automatic monitoring system for bridges and buildings to detect earthquakes as well as to detect structural anomaly using a wireless accelerometer network is presented. The daily periodic ambient data is considered as a reference to evaluate the performance of the structures through changes of dynamic characteristics such as natural frequencies, modal shapes, and inclination of the structures along the time. An original algorithm was developed to accurately estimate natural frequencies and modal shapes with a high efficiency event with less than 1 gal level of acceleration in ambient vibration. A step-by-step approach was developed to evaluate the structure in real-time after the seismic event.

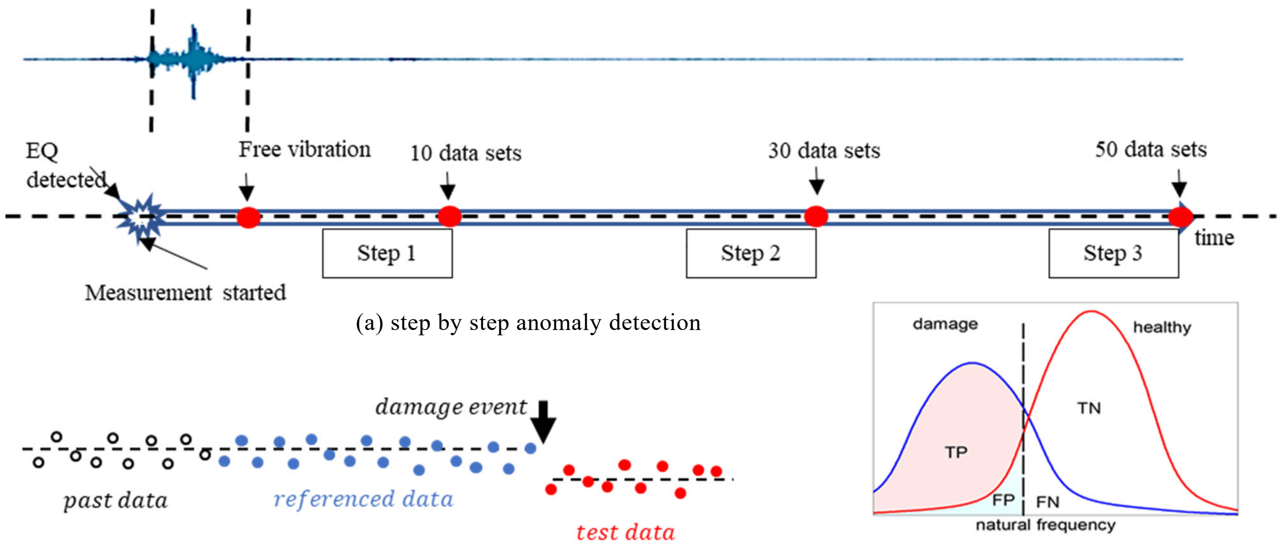
2. MONITORING SYSTEM FEATURES

2.1 SEISMIC DETECTION AND SCHEDULED MEASUREMENT

Civil structures such as bridges and buildings are generally of considerable size, making the installation of wired systems costly and not desirable. Especially, in bridges, it is difficult to layout the cable of wired sensors. For these reasons, a wireless monitoring system as shown in **Fig. 1** was developed to enable to monitor bridge and building structures. The system consists of several triaxle accelerometers at critical locations and one or several trigger nodes for seismic event real-time detection. Sensor nodes are communicated in a wireless network and driven by dry batteries. Measured acceleration is sent to the cloud server in order to give easy access to inspectors and to allow abnormal detection creating a real-time monitoring system. Email notification function is also included to notify the inspector about the seismic event detection. In operation, accelerometers at sensor nodes measure vibration at a predefined schedule to make referenced data for structure evaluation. The trigger node, on the other hand, measures continuously with solar power support to monitor vibration in seismic events. Besides 3 axial acceleration, inclination angles and temperature are also recorded. With wireless sensors and compacted size of sensors, this system proves to have large freedom to set up in bridges, buildings, and other infrastructures.

2.2 STRUCTURAL IDENTIFICATION

Structural identification for monitoring context is the process of estimating dynamic characteristics of structures using measured data. The process can be done in a forward problem with analytical structural models that can be calibrated for a targeted structural condition, to calculate structural properties. However, it is difficult to calibrate the structure, the inverse problem is more common in structural health monitoring. The inverse problem can identify the structures without the FEM model. In this paper, the structural properties can be identified using the structural response measured data only, without considering input for those responses which is hard to measure for bridges or buildings under in-service conditions. Particularly, the dynamic modal properties such as natural frequencies, modal



(a) step by step anomaly detection

(b) structural characteristic change in damage

(c) statistic model for anomaly detection

Fig. 2. Anomaly detection concept

shapes, and rotation angles are estimated from acceleration data by fundamental spectrum analysis. Fast Fourier transform was firstly applied to acceleration, then an algorithm was developed to estimate frequencies and modal shapes of the structure from the acceleration spectrum. This algorithm can identify the dynamic properties even with low amplitude vibrations.

2.3 ANOMALY DETECTION

Anomaly in this context refers to sudden changes in structural properties, such as reduction of natural frequencies, change in modal shapes, etc., due to cracks, deterioration. The natural frequencies and modal shapes are functions of structural weight and stiffness; hence, a reduction in natural frequency may indicate a stiffness reduction due to damage or mass change in structures. However, for a long term period, environmental factors, such as temperature, are varying in time causing the dynamic properties could fluctuate within a range. These fluctuations may overlap with the small changes of frequencies due to light cracks or damages. Therefore, it is necessary to remove this effect in order to detect small damages. In this monitoring system, scheduled measured data is used as a reference to detect anomaly after hazard events or long-term variations. Whenever a seismic event detected, the system will form a referenced state by a normal distribution model using scheduled data measured before the event. Similarly, a normal distribution model for the test state will be also created by data after the detected event. If the statistical distribution model changes, damage or anomaly is potentially identified. For example, in the undamaged condition, each frequency can be represented by the normal distribution. The distribution would move to the left when damage occurs as shown in **Fig. 2(c)**. To enable real-time anomaly detection, three-step processes for detection, later steps target for smaller changes, was developed to detect anomaly as in **Fig. 2(a)**. By optimizing the threshold in the outlier test, the system can detect such small changes in the range of 1.5 times the standard deviation in the natural frequency distribution. Changes in modal shapes were evaluated by Modal Assurance Criterion (MAC), calculated as per equation (1), where $\emptyset_i$ and $\emptyset_0$ are modal shapes at evaluated time and reference mode shape vector. MAC indicates the modal shape change when it becomes below 1.0.

$$\mathrm{MAC}(i)=\frac{(\phi_0^T\phi_i)^2}{(\phi_0^T\phi_0)(\phi_i^T\phi_i)} \tag{1}$$

3. APPLICATION IN CIVIL STRUCTURES

The system was applied in two highway bridges in Japan. The first bridge is the Mukogawa Bridge which is a highway bridge in the Shin-Meisin Expressway, Japan, as in **Fig. 3**. This is the first extradosed butterfly web bridge in the world with 5 continuous rigid-frame span prestressed concrete box girder. The total bridge length is 442m with a typical span of 100m. The bridge was awarded in the finalist of outstanding structures by IABSE 2019. A vibration monitoring system was installed in 2016 right after the construction of the superstructure to measure bridge ambient vibration

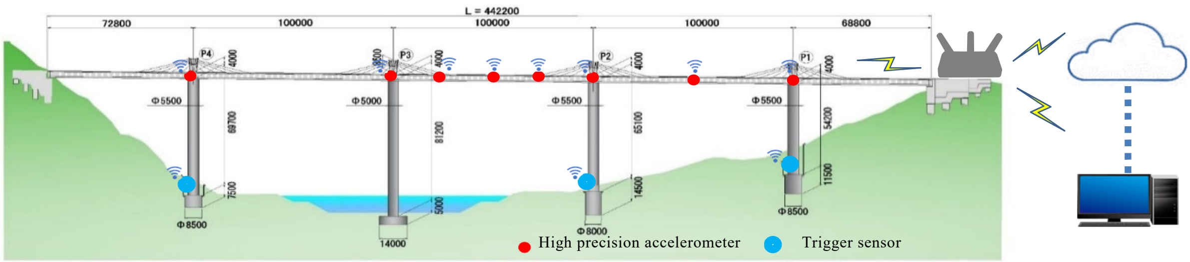


Fig. 3. Monitoring system in the Mukogawa Bridge

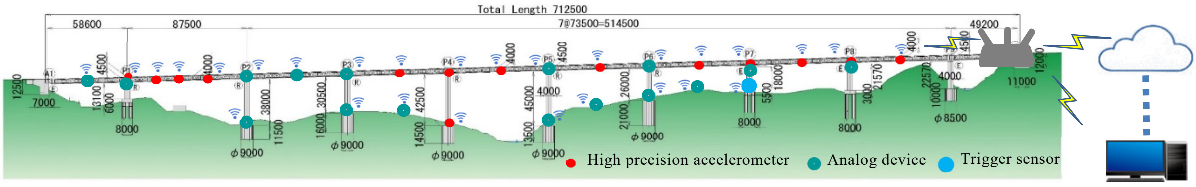
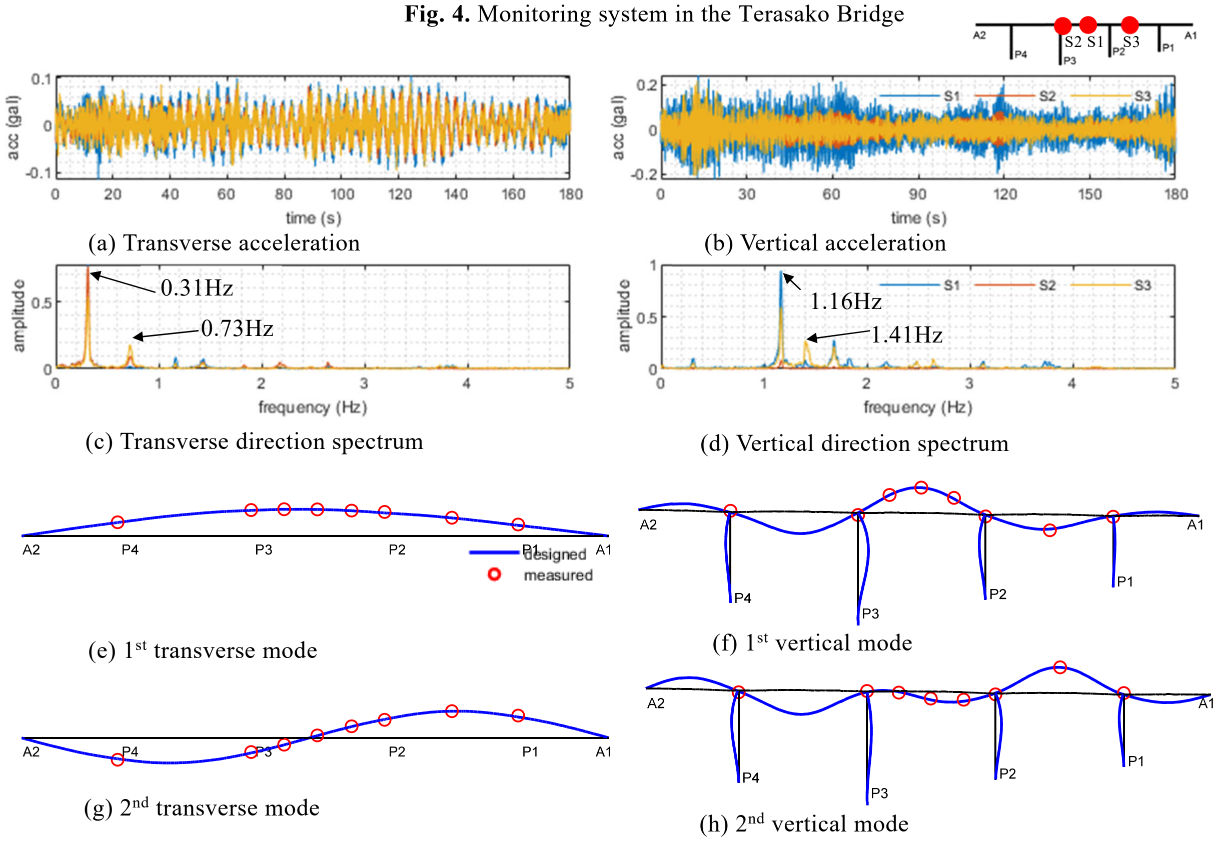


Fig. 4. Monitoring system in the Terasako Bridge



(a) Transverse acceleration

(b) Vertical acceleration

(c) Transverse direction spectrum

(d) Vertical direction spectrum

(e) 1st transverse mode

(f) 1st vertical mode

(g) 2nd transverse mode

(h) 2nd vertical mode

Fig. 5. Structural identification result

acceleration during road surface construction period as well as after the bridge opens to traffic. Vibration in ambient daily traffic, as well as vibration in such seismic events like earthquakes, is monitored. A total of 17 wireless accelerometer nodes, driven by dry battery, were set up in girder to measure vibrations of the bridge. Three trigger nodes were set at bottom of pier to monitor unusual large vibration due to earthquake, strong wind, or another large excitation. Those trigger nodes, powered by solar battery, are continuously measuring to detect any large vibration. Accelerometers are scheduled to measure vibration two times every day for making referenced data. Measured acceleration will be sent to cloud server in order to give easy access to inspectors and to allow abnormal detection that can be automatically implemented in the server creating a real-time monitoring system. Email notification function is also included to notify the inspector whenever trigger nodes detect a seismic event.

A similar system was set up to the second bridge, the Terasako Choucho Bridge (previously called the Takubogawa Bridge) as shown in **Fig. 4**. This is the first rigid-frame butterfly web girder bridge in the world, located in the Highashi Kyushuu Expressway in Hyuga city, Miyazaki prefecture, Japan. In 2016, it was recognized as an outstanding structural award by FIB. The bridge has a 10-span continuous prestressed concrete box girder with a typical span of 73.5m and a total length of 712.5m. A total of 28 accelerometers was setup to monitor the bridge. One trigger node was also installed in pier P7 for earthquake detection. The sensor network and its operation are the same as with the Mukogawa Bridge.

4. RESULT AND DISSCUSION

4.1 STRUCTURAL IDENTIFICATION

Whenever acceleration data is uploaded to the cloud, the structural identification process is implemented to estimate natural frequencies and modal shapes. **Fig. 5** shows an example of structural identification results for the Mukogawa Bridge on a slightly windy day before the bridge opening to traffic. The identified mode shapes are well consistent with designed values. It confirmed that event under micro-vibration with acceleration less than 1 gal, the natural frequencies, and mode shapes can be estimated accurately. Furthermore, it showed that when there is not car moving on the bridge, it is hard to identify natural frequencies because of the high white noise ratio. An algorithm to find the most reliable peaks was developed to estimate natural frequencies by statistical processes. It showed that dominant frequency peaks vary when no traffic running in the bridge, but the natural frequencies can be estimated efficiently from the dominant peaks as shown in **Figs 8, 12**.

4.2 EARTHQUAKE DETECTION

Detecting earthquake and intensity estimation was designed as a key function of the monitoring presented in this paper. The trigger nodes setting at the pier lower part track the occurrence of earthquakes with solar power supply. The monitoring system presented in this paper detects seismic events by tracking RMS acceleration in the trigger nodes. During the monitoring term from December 2017 up to March 2020, in the Terasako Choucho Bridge, there were several medium to major earthquakes as recorded in **Table 1** [11]. All of these seismic events were detected by this monitoring system. **Fig. 6** shows the maximum acceleration in daily measurement as well as in detected earthquakes in the monitoring system in the bridge. It confirmed that the system can detect all listed earthquakes.

4.3 GEOMETRY INCLINATION

The acceleration vector has a trigonometric relationship

Table 1. Recorded earthquakes by Japan Meteorological Agency

No	Epicenter name	Time	Maximum intensity	Intensity at Hyuga
1	Hyuga	2019/5/11 8:59	4	2
2	Hyuga	2019/5/10 9:07	3	2
3	Hyuga	2019/5/10 8:48	5-	3
4	Hyuga	2019/5/10 7:43	3	2
5	Hyuga	2019/3/27 15:38	4	3
6	Hyuga	2019/3/27 9:11	3	3
7	Kumamoto	2019/1/3 18:10	6-	1
8	Hyuga	2018/7/3 20:38	3	2
9	Hyuga	2018/2/9 3:31	4	2

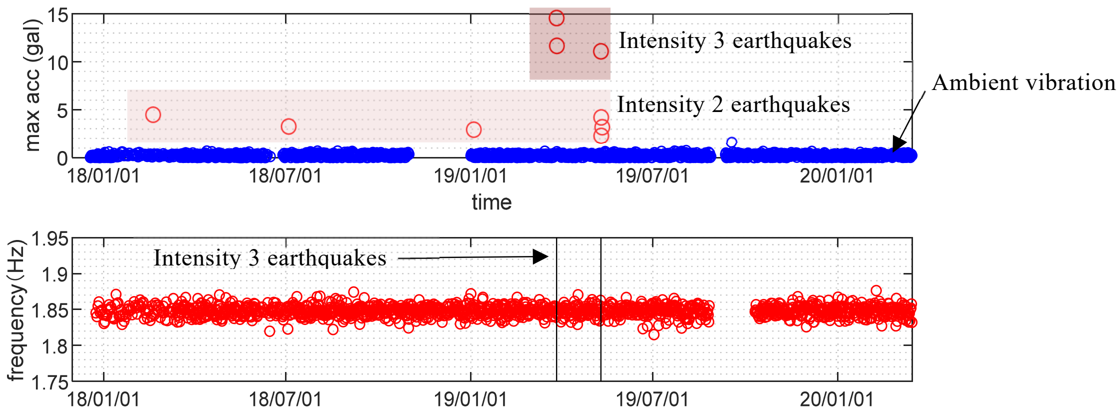


Fig. 6. Earthquake detection and filtered frequency in the Terasako Choucho Bridge

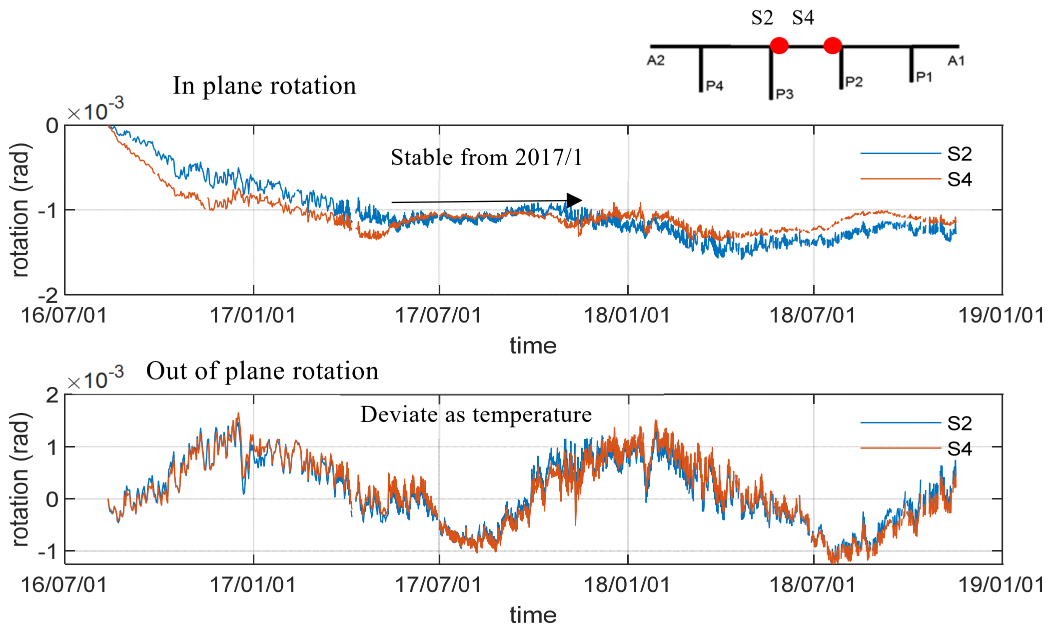


Fig. 7. Inclination variation in the Mukogawa Bridge

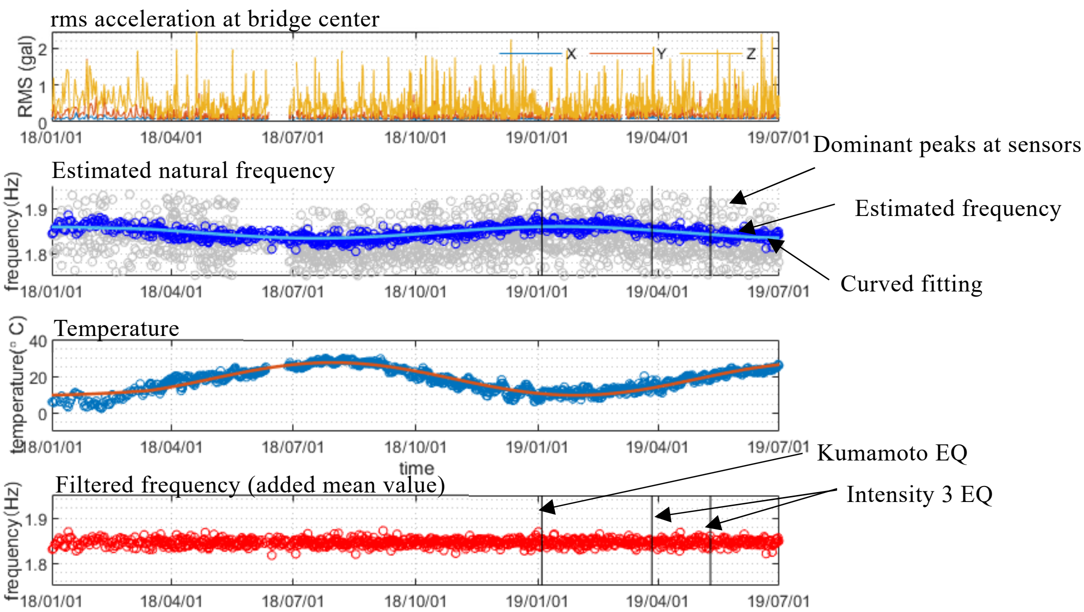


Fig. 8. 2^{nd} vertical mode frequency variation and anomaly detection in the Terasako Choucho Bridge

with the gravity vector, that allows defining tilt angle of accelerometers. Once structure deforms due to concrete creep, foundation settlement, etc., the structural inclination would be changed, making it possible to detect the long-term deformation in structures. **Fig. 7** presents the inclination of the Mukogawa Bridge girder since the superstructure construction completed. It found a minor change in inclination in both bending direction (in-plane rotation) as well as transverse direction (out of plane rotation). In-plane rotation progressed from the beginning of measurement and became stable from 2017/01. This deviation may have caused by creep effect. In out of plane rotation, the movement is consistent with the variation of temperature. However, the both movements are very small, approximately 1 milliradian. It also confirmed that there was not abnormal deformation due to the foundation settlements of the bridges.

4.4 ANOMALY DETECTION

It has been almost 2 years since the system started measuring at the Terasako Choucho Bridge. **Fig. 8** shows the variation of 2nd vertical mode frequency variation from December 2017 together with the temperature variation until

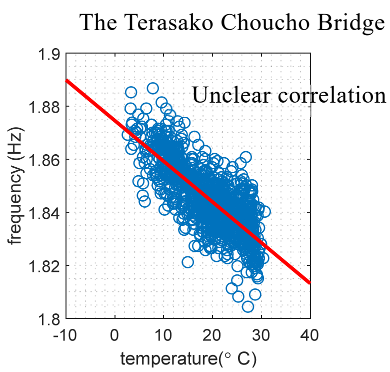


Fig. 9. Temperature versus frequency

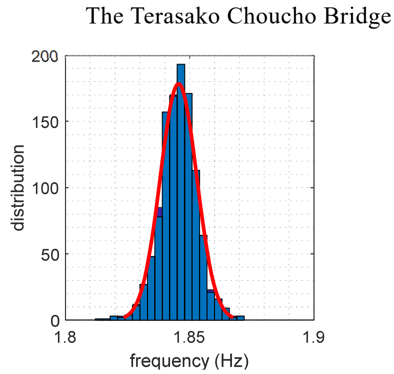


Fig. 10. Filtered frequency distribution

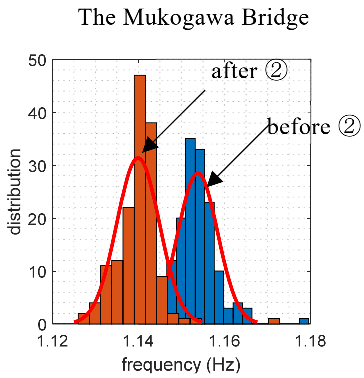


Fig. 11. Filtered frequency distribution before and after ②

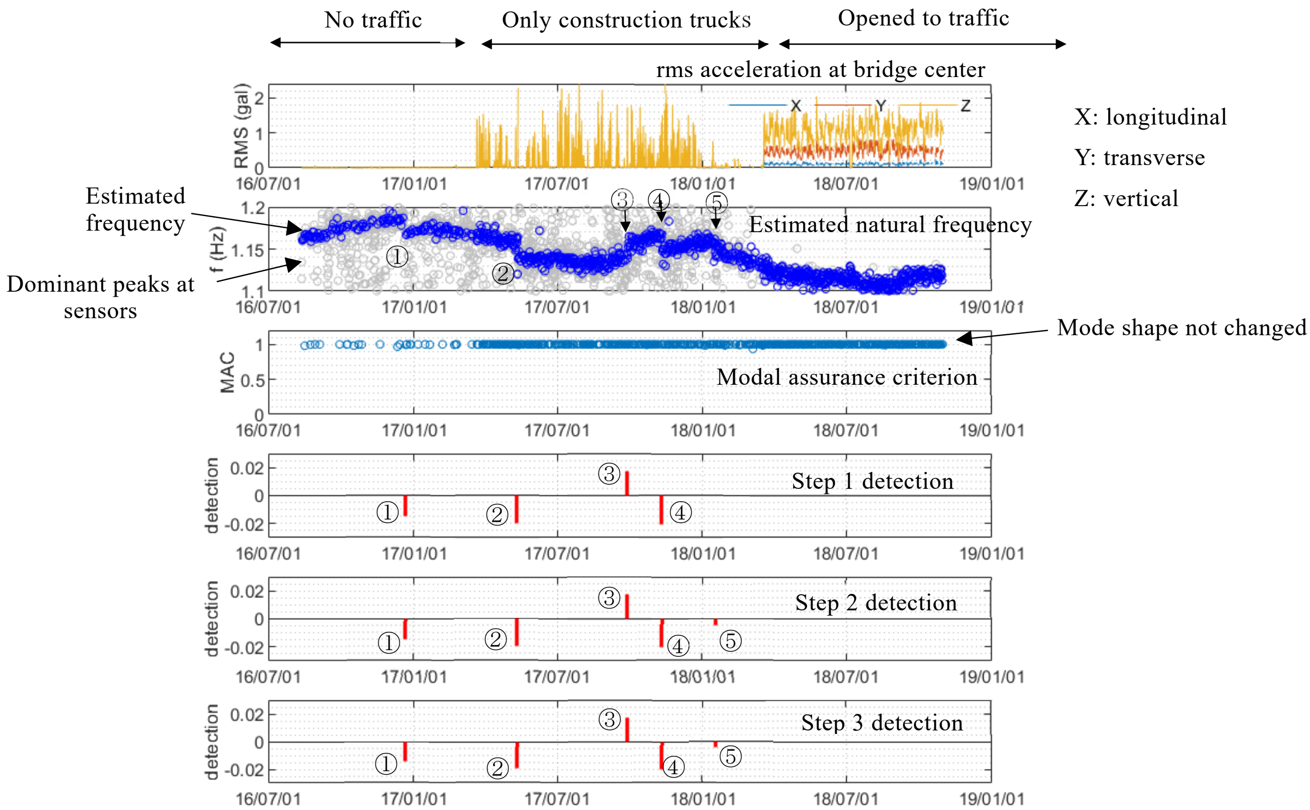


Fig. 12. 1st vertical mode frequency variation and anomaly detection in the Mukogawa Bridge

July 2019. It shows that due to the changing environment condition during the year, the frequency also varies following a yearly cycle, but with a time lag compared to temperature. The temperature has a major effect on the variation of frequency. Furthermore, the change of frequency due to temperature change is relatively large, close to 2-3 times of standard deviation of frequency in measurement. These long-term variations may overlap with the small changes of frequency due to light cracks or damages. Therefore, it is necessary to remove this effect in order to detect small damages. The temperature effect can be suppressed assuming a linear relationship between temperature and frequency as shown in **Fig. 9**. However, this approach has low accuracy because frequencies have a short time lag to temperature change and it requires a year-long measurement to gather enough representative data. Instead, in this paper, a high-pass filter was used to remove the effect of temperature. The high pass filter was designed in order to remove low- frequency movement as year cycle due to seasonal change. The mean value of few latest measurement frequencies was used in combination with filtered frequency to form a reference statistical model to track anomaly. The Terasako Choucho

Table 2. Construction recorded work for road surface finishing

No	Time	Content
①	2016/12/21	Temporary asphalt
②	2017/5/12	Outbound line leveling layer
③	2017/9/28	Remove temporary asphalt
④	2017/11/10	Inbound line leveling layer
⑤	18/01/18-26	Asphalt surface layer

Bridge experienced three level-3 intensity earthquakes during the last two years, however, as shown in **Fig.8** the frequency has not changed after those hazard events. It means that there may be not cracks or damage by the hazard event. Furthermore, **Fig.10** plotted histogram for 2-year natural frequency shows that the initial assumption of the normal distribution model of natural frequency is reasonable.

In the Mukogawa Bridge, the natural frequencies of the bridge move with a similar pattern along the year due to the change in temperature. However, the monitoring system in this bridge was installed right after the concrete construction was completed. There were some construction works related to asphalt surface finishing still remain at that time. **Table 2** shows a record of these works. Due to asphalts layers added, the weight of the bridge was increased and the bridge natural frequency changed consequently, as an example in **Fig.11**. The step-by-step algorithm can detect these small changes as shown in **Fig.12**. At the event ① to ④, the change of frequency is relatively larger and it can be easily appreciated. At event ⑤, frequency changed slightly because only asphalt surface layer was added in the bridge, but the monitoring system can also detect this change.

5. CONCLUSION

In this paper, an automated monitoring system to detect seismic events and detect anomaly for buildings and bridges using wireless sensor networks is introduced. The system is able to detect seismic events such as earthquakes and typhoons and then detect structural anomaly in real-time. Its application to two real highway bridges confirmed that it can detect all earthquakes of the targeted magnitude. The system can identify modal properties efficiently, event under very low excitation such as traffic, wind, or white noise excitations. The statistic models of modal properties are developed to represent structural characteristics and detect structural anomaly. Furthermore, the application of high pass filter can be used to remove the effect of temperature, so that smaller changes in modal properties can be detected easily, creating feasibility of small damage detection. This system could be applicable to both bridges and building structures for structural health monitoring after seismic events as well as long term performance monitoring.

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