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A Study on the Detection of Bridge Slab Deterioration Using a Wireless Vibration Measurement System

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ABSTRACT: The vibration characteristics of structures have been considered to be one of the important evaluation indices to diagnose the deterioration of the transportation infrastructure accurately. The purpose of this study is to develop the investigation technology by using a wireless vibration measurement system which can be implemented easily. Base on the changes of the vibration characteristics obtained from measurement, the differences between healthy and deteriorated slabs can be ascertained. In this paper, a measurement experiment is implemented in an in-service condition bridge. Frequency, vibration modes and displacement are analyzed for finding the vibration characteristics and finite element analysis is performed to confirm the validity of the measurement results. Comparing with the response properties of slabs, it is considered that the position of the slab that is deteriorated can be detected. Though it is only one measurement result, the effectiveness of this method in ascertaining the vibration characteristics and detecting slab deterioration of bridge slabs is confirmed in this study.

1 INSTRUCTIONS

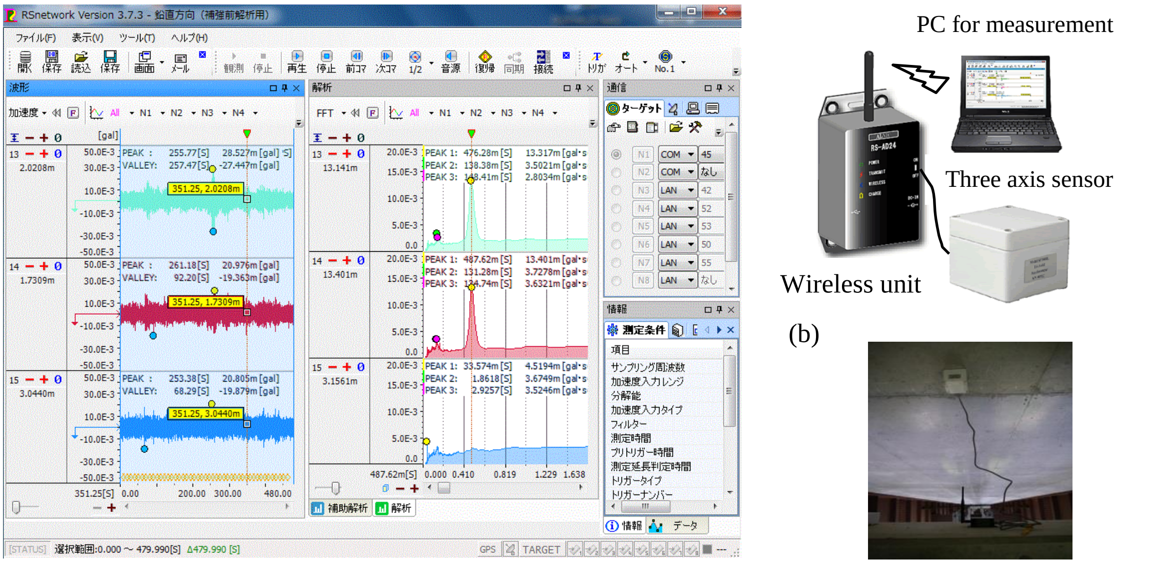
In Japan, many transportation structures have been built since the high economic growth period. From the viewpoint of ensuring the road networks, they have played a big role in the convenience of city life and have been indispensable for people's lives. However, these transportation structures are constantly exposed to heavy vehicles and high speeds in recent years, beyond what was expected when they were constructed. Deterioration and damage due to fatigue by traffic vibration are concerns. So it is necessary to identify the health of road and bridge structures effectively so that they can offer service continuously, and studies about the vibration characteristics of road and bridge structures have been performed energetically (Li et al. 2014; Loh et al. 2007). It is considered as a more objective evaluation method for the health of bridge slabs that focusing on the vibration characteristics such as the natural frequency and modes between healthy and deteriorated slabs or before and after the slab is deteriorated. The Ministry of Land, Infrastructure and Transport in Japan has set up “a committee for the promotion of monitoring technology in social infrastructure” in 2013, and the inspection technology of civil engineering structures has been promoted (Japan Ministry of Land, Infrastructure and Transport. 2013). The convenience of wireless measurement has also been discussed (Yang et al. 2006).

In this paper, the effectiveness of this measurement system is verified and a damage scanning method for the bridge slab using inspection passage is proposed. In addition, the bridge superstructure is modeled and eigenvalue analysis is performed to confirm the validity of the measurement results. Based on the results of measurement and analysis, natural frequency, displacement and vibration modes can be evaluated accurately and easily by using this wireless measurement system. Furthermore, a comparison of the differences of an in-service condition of highway bridge slab's vibration characteristics, deterioration may be detected and located. This paper presents the laboratory findings of an in-service condition bridge which isn't aging while many cracks have occurred.

2 EXPERIMENT SUMMARY

2.1 Measurement system

This wireless acceleration measurement system was developed by Hiroshima University and a private enterprise. Photo 1 shows the measurement system. The measurement machines are composed of commercial servo type acceleration sensors and wireless transmitting units which were developed. A wide range of vibration characteristics of structures can be measured with a high accuracy, from microtremors up to 3000 Gal. Measurement and analysis software was developed also at the same time. Table 1 shows the specification of this measurement system. The major feature of this system is that wiring is unnecessary, vibration measurement of in-service condition roads and bridges can be performed without traffic regulation if by using the inspection passage. And the sensors can be attached by using strong double-sided tape as shown in Photo 1 (c).



(a) (c)

Photo 1. The measurement system (a) Vibration measurement and analysis software (b) measurement equipment (c) mounting of the sensor

Table 1. Specification of the measurement system

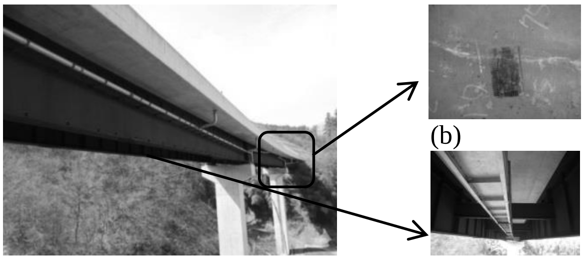
Item	Specification
Measurable range	±3000gal
Sampling frequency	100, 200, 500, 1000sps
Resolution	24bit
Detection axis	3-axis, simultaneous AD conversion
Communication system	Radio communication system, Bluetooth class 1
Number of Simultaneous connect	7
Analysis	FFT (fast Fourier transform), displacement conversion, vibration mode, etc.

2.2 Measurement and analysis method

In order to ascertain the vibration characteristics of the object bridge, a measurement experiment was carried out by setting a plurality of different cases. The measurement sampling frequency is set to 100 Hz and the acceleration input type is direct current. Take the simple average of 20.48 seconds of data from the measurement data, measured for 5 minutes, to perform Fourier spectrum analysis. In addition, use a filter and lissajous function (three dimensional wave synchronous displays) to extract vibration modes of a typical acceleration. In order to identify vibration modes accurately, a finite impulse response digital filter is used. Eigenvalue analysis is performed by using finite element method (FEM) for a comparison of the measurement results.

2.3 The object bridge

Photo 2 shows the object bridge of this measurement experiment. It was built in Shimane, which is located in the southwest of Japan's mainland and faces the Sea of Japan. Construction was completed in 2010, however cracks have been observed and the deterioration position is shown in Photo 2 (b). The superstructure is a three-span continuous non-composite steel bridge with cast-in-place precast concrete (PC) slabs. Its length is 143.0 m and the width is 11.17 m, according to the blueprint. The cracks were confirmed by visual inspection before the measurement experiment was implemented, and the measurement plan was conducted according to the inspection results.



(a) (b) (c)

Photo 2. Observation bridge (a) bridge appearance (b) crack in the slab (c) inspection passage.

2.4 *Measurement cases*

A simple drawing of the bridge and the position of sensors are shown in Figure 1. To ascertain the vibration characteristics of the whole bridge, sensors were placed in the direction of the bridge axis as in Case 1, shown in Figure 1 (a). Case 2 and Case 3 are to compare with the difference between slabs in with and without cracks. In case 2 and case 3, sensors were placed in the direction perpendicular to the bridge axis and were set about 1.0 m from the inspection passage.

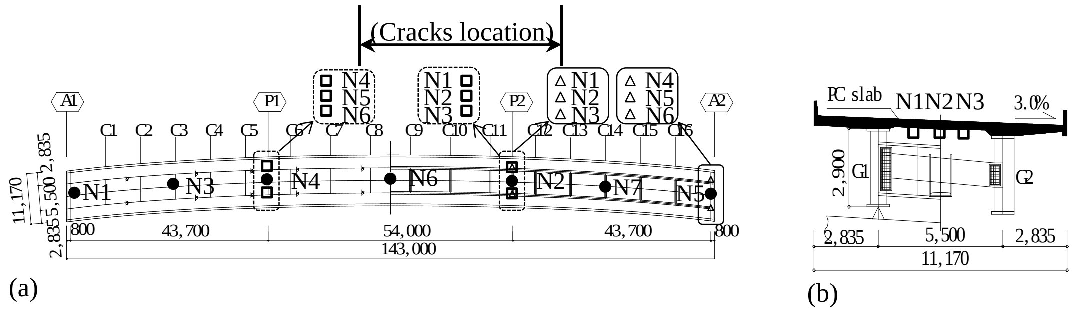


Figure 1. Bridge drawing and sensor setting cases (a) plan of the bridge (b) cross section of P2 (Case 1:●, Case 2: □, Case 3: △).

3 EXPERIMENT RESULTS AND DISCUSSION

3.1 *Measurement results*

In the measurement of Case 1 shown in Figure 1 (a), measurement data obtained from the experiment performed in 300 seconds, overlapped in 50% and then divided into small sections of 20.48 seconds to perform fast Fourier Transform (FFT) analysis. Figure 2 shows the Fourier spectra of Case 1. The results of center of spans are shown in Figure 2 (a); the results of the intermediate supporting point are shown in Figure 2 (b). In the center of the spans, the natural frequency is observed in 2.34 Hz, 4.3 Hz, 9.77 Hz, 14.45 Hz and 18.75 Hz, and in the intermediate supporting points it is seen that in 14.45 Hz and 18.75 Hz, the acceleration response is the largest. According to Figure 2 (b), the response acceleration and natural frequency are exactly the same; it is difficult to identify the deterioration which had occurred near the bridge pier P2.

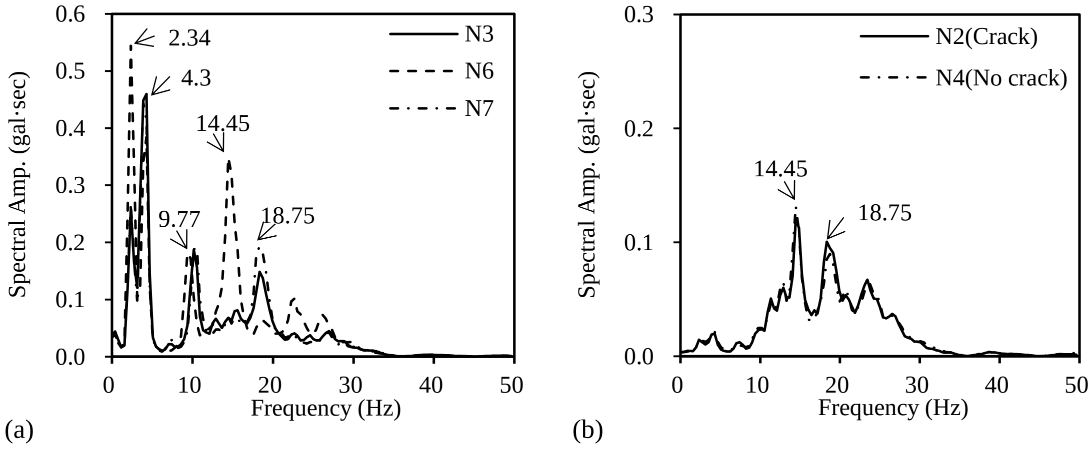


Figure 2. Fourier spectral (a) center of spans (b) intermediate supporting points.

3.2 Comparison between eigenvalue analysis and measurement results

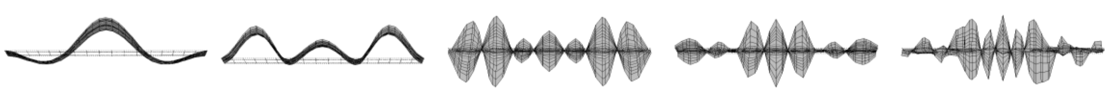
According to studies of the past, it is possible and effective to evaluate the damage of a whole bridge quantitatively from the change in its natural frequency, but the difficulty of applying this method to minor and localized damage is also recognized. So it is important to understand the vibration characteristics, such as vibration modes, displacement and so on, if the bridge slabs are not very deteriorated. A simple method has been proposed in this study to estimate the vibration modes of bridge slabs and is applied to transportation structures. The method is that according to the frequency peaks from FFT analysis; a band pass filter with a width of 0.2 Hz is applied to extract the vibration modes. The vibration modes gleaned from measurement data are shown in Figure 3 (a). From the modes, each vibration frequency can be confirmed accurately. It is expected that we will be able to estimate the location of progressing damage in bridge slabs from the changes in the natural frequency and modes if regular measurements are performed.

In order to verify the validity of the measurement results, eigenvalue analysis is performed by FEM. The object of FEM analysis is superstructure, and it is assumed that the end of bridge is fixed; the central fulcrum is pin support because the deadweight of the bridge slab is heavy. The analysis model is built approximately, as there is no detailed design data or information of the aging situation. The vibration modes obtained from FEM analysis are shown in Figure 3 (b).

According to the comparison results shown in Figure 3, the consistency of the vibration modes obtained by measurement and FEM analysis is confirmed. Especially in the lower order modes, the same vibration mode shapes are seen. However, a variation in the frequency is observed due to the simplification of the FEM analysis model, and the difference is lager in higher order modes. Therefore it is possible to ascertain the vibration characteristics of bridge slabs by using the wireless measurement system, and the reliability of the measurement results is confirmed, though it is necessary to set more sensors to understand the local vibration modes of a bridge slab (Japan Society of civil Engineers. 2010).

2.34 Hz 4.30 Hz 9.77 Hz 14.45 Hz 18.75 Hz

(a)



2.22 Hz 4.54 Hz 9.09 Hz 11.1 Hz 14.29 Hz

(b)

Figure 3. Comparison of analysis results (a) results of measurement (b) results of FEM.

3.3 Proposal of a deterioration evaluation method

Many methods have been proposed to grasp the vibration characteristics from the vibration response of traveling vehicles (McGetrick et al. 2014). In this study, a method of detecting the deterioration of bridge slabs focusing on the changes of vibration characteristics caused by vehicle vibration is proposed. Thus, it is difficult to judge the deterioration position of bridge slabs in microtremor vibration level, the difference between healthy slabs and deteriorated slabs can be identified when the same vehicle is passing. By setting the wireless acceleration measurement system in the inspection passage under bridge, the experiment can be performed without blocking traffic.

About the object bridge, many cracks were observed near pier P2 by visual inspection. In order to identify the difference between a healthy slab (N5 set position) and a deteriorated slab (N2 set position), power spectra and displacement are analyzed from the data when a vehicle is passing. Figure 4 shows the power spectra and Figure 5 shows the displacement when a vehicle crossing. The result of power spectra shows that vibration response of deteriorated slabs is approximately 2 times larger than that of a healthy slab when the same vehicle is crossing. Thus, it is not seen in Figure 2 because the result is obtained from the average of data. Therefore it is possible to identify abnormalities in slabs when a vehicle is passing, rather than through microtremor vibration. Furthermore, the displacement in Figure 5 shows a similar trend, although the difference is small.

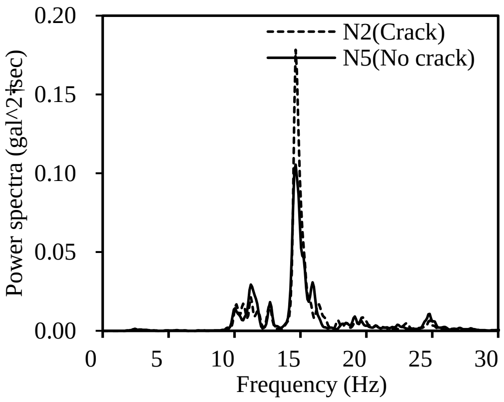


Figure 4. Power spectra when a vehicle is crossing.

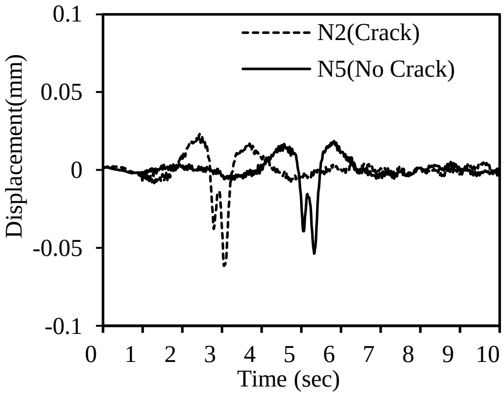


Figure 5. Displacement when a vehicle is crossing.

According to the reported findings, slabs can easily deteriorate within the superstructure from the fatigue caused by traffic vibration, and it is believed that the deterioration of the central slab in the direction perpendicular to a bridge's axis is large. Therefore if the abnormality is found in the response characteristics of the central portion on both sides of the slab or bridge girder, it is useful in detecting and locating the deteriorated portion. In this study, the displacement magnification of the central slab to both sides of the slab is calculated as a method for detecting the deterioration of a slab. Also, in order to eliminate the influence of vehicle crossing positions, the average value of both sides is used. Figure 6 shows the displacement magnification of the central slab to the average of both sides in Case 2 and Case 3. The vertical axis shows the displacement magnification when vehicles are crossing and the horizontal axis shows each small section, T1 to T7. In every section, the magnification appears larger where cracks have occurred, though some variation appeared in the T6 section. Although the displacement of both sides slab is dominated by the bridge girder, it is believed that the deterioration of a slab can be reflected directly by the displacement of the central portion. The difference in the displacement magnification is small because the bridge was built in 2010, but the trend obtained from Figure 6 shows that it is possible to detect the deterioration of bridge slab with this evaluation method.

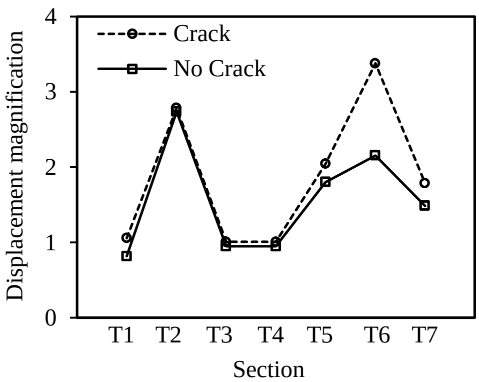


Figure 6. Displacement magnification (Case 2 and Case 3).

4 CONCLUSIONS

In this experiment, with the cooperation of the Japan Ministry of Land, Infrastructure and Transport Chugoku Regional Development Bureau, vibration measurement was performed on a bridge using a wireless acceleration measurement system. The findings obtained from this experiment are as follows.

(1) It is unnecessary to cut off traffic when performing vibration measurement when below in the inspection passage, and by using the wireless vibration measurement system; it is possible to reduce the time and human power of bridge inspections.

(2) By using this wireless vibration measurement system, it is possible to estimate the complex vibration characteristics of the bridge slab and the validity of the measurement results have been confirmed via FEM analysis. However, in higher order vibrations, it is necessary to set more sensors to accurately obtain the vibration modes.

(3) The difference between the vibration response and displacement in healthy and deteriorated slabs when a vehicle is passing is observed, though it is difficult to judge from the frequency. The method by comparing with the displacement magnification of central slab to the average of both sides slab is considered to be effective for detecting the deterioration of bridge slabs. In the

future, it is important to accumulate data and improve the method to ensure the reliability of this evaluation method through increased measurement examples.

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