Development of Bridge Monitoring System for Short- and Medium-Span Bridges based on Bus Vibration

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ABSTRACT: In our country, because there are a huge amount of existing short- and medium-span bridges in service, it is becoming one of major social concern how those bridges can be maintained in good condition during their whole lifetime. In this paper, a method of the condition assessment is proposed newly for existing short span (10m～20m span length) RC bridges based on monitoring data from public bus vibration. This paper describes the details of not only a prototype monitoring system using information technology and sensors which is capable of providing more accurate knowledge of bridge performance than traditional ways but also a few specific examples of bridge condition assessment by public bus vibration measured in operating on the bridge based on the data from the system.

1 INTRODUCTION

In order to periodically inspect and properly maintain a large number of short- and medium-span bridges in Japan, it is necessary to develop a simple and efficient bridge monitoring system. The authers have been developing a new method of assessing the condition of exisisting short- and medium-span bridges based on vibration monitoring data obtained from a public bus(see Fig. 1) (Miyamoto & Yabe(2012)). The aim of this paper is to introduce the validation experiment for a short- and medium-span bridge monitoring system which is newly developed to evaluate bridge conditions through vibration measurement conducted by using a publicly operated fixed-route bus, and describes the validation results and various findings related to the practical use of the system in the coming years. An acceleration sensor is installed under the rear spring of a fixed-route bus, and characteristic deflection is calculated from the vibration measured when the bus passes over a bridge. If the vibration thus measured reaches a certain level, it is judged that the bridge is in a serious condition of one kind or another. In such cases, a detailed visual inspection is conducted as soon as possible, and appropriate repair or strengthening measures are taken. In the validation experiment conducted in Ube City, Yamaguchi Prefecture, Japan, a sensor was installed to an in-service fixed-route bus, and a total of 39 measurements were conducted over a period of about one year from December, 2010. As the first step, the bridges existing on the routes of the fixed-route bus service operated by Ube City were counted, and bridges to be monitored and a fixed-route bus to be used were selected. Comparison of the measured under-rear-wheel-spring acceleration response of the bus and the measured midspan-of-girder acceleration response of each bridge revealed that when passing over a bridge, the passing bus causes the bridge to vibrate. As the next step, characteristic deflection was calculated by determining displacement by integrating the under-rear-wheel-spring acceleration twice. As shown in Table 1, weather, the number of oncoming vehicles, the number of occupants and bus speed were recorded to evaluate the influence of operating conditions on characteristic deflection.

Vehicle-induced vibration simulation by the “substructure” method(Yabe(2006)), which is a finite element method, was also conducted for the selected bridges to determine deterioration evaluation criteria. In the vehicle-induced vibration simulation, differences in calculated values of characteristic deflection and the structural abnormality parameter between different analysis models were evaluated. Finally, the degrees of abnormality of the monitored bridges were expressed with the "inspection necessity level" to enable local governments to prioritize their bridge maintenance needs quantitatively.

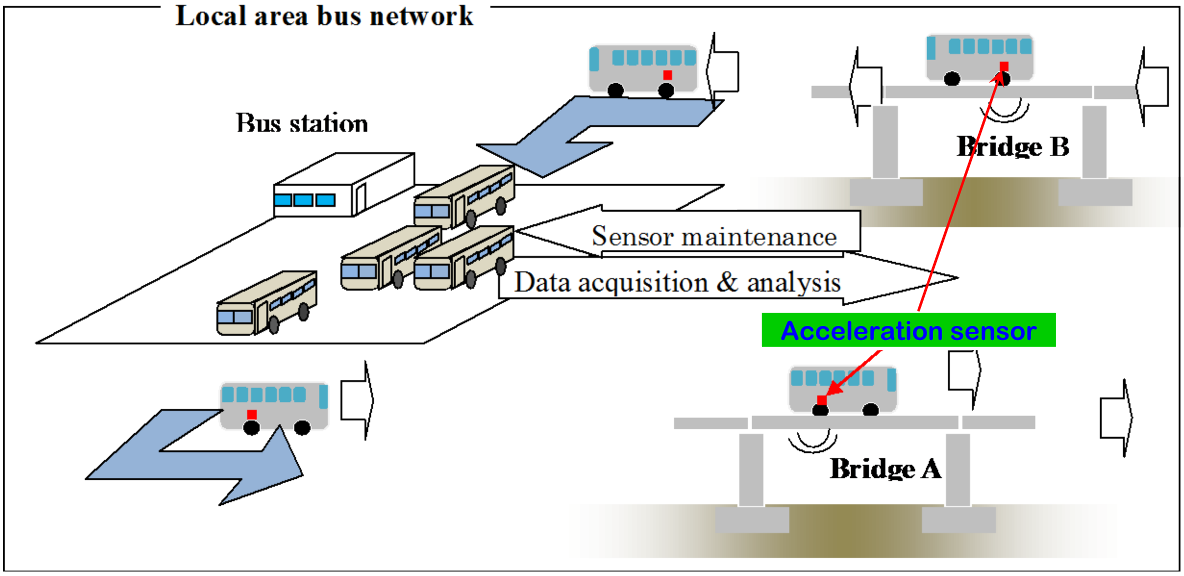


Figure 1. Concept of bus monitoring system for short- and medium-span bridges

Table 1. Operating conditions considered in validation

Weather	Clear, cloudy, light rain or rain
Number of oncoming vehicles	Number of vehicles coming from the opposite direction while the rear wheels are passing over the bridge
Number of occupants	Including the driver
Bus speed	Reading of speedometer

2 CALCULATION OF CHARACTERISTIC DEFLECTION

2.1 Validation experiment in Ube City

2.1.1 Number of bridges on bus routes

Prior to the experiment, the bridges in Ube City on the routes of the buses operated by the municipal department of transportation were identified to select bridges(Ube Municipal Government(2011)) to be monitored. The results are shown in Fig. 2. Out of a total of 413 bridges (15 m or longer) managed by Ube City, 38 bridges were found to be located on the bus routes. The bridges existing on the routes account for only 10% of the total, but if the newly developed monitoring method is put to practical use, it is possible to apply the method to those bridges by, for example, running fixed-route buses for the purpose of bridge inspection. Although this study focused only on the bridges managed by Ube City, the new monitoring method can be applied to more bridges because it can also be applied to other bridges managed by Yamaguchi Prefecture and bridges located on privately owned land.

2.1.2 Overview of experiment

Table 2 summarizes information on the validation experiment. The validation test was conducted over a period of one year from December, 2010, with the cooperation of the Civil Engineering and Construction Department and the Department of Transportation of Ube City. The bridges to be monitored and bus routes were selected so that the monitoring bus passes over the Jyase Bridge, which has more spans (5 spans) than any other bridge on the bus routes, as often as possible. This study focused on the Jase Bridge, Shiratsuchi Daini Bridge and the Shingondai Bridge so as to increase the number of measurement passes as much as possible. Information on the three bridges is summarized in Table 3.

2.1.3 Experiment method

In the validation experiment, an acceleration sensor was installed under the rear wheel spring of an in-service fixed-route bus, and the deflection of each bridge when the bus passed over it was estimated from the acceleration response of the bridge. The specifications of the bus and acceleration sensor used in the experiment are summarized in Tables 4(a) and (b). The acceleration sensor installed under the rear wheel spring of the bus is shown in Fig. 3. The acceleration sensor was bonded to the underside of the rear wheel spring and coated with epoxy resin for protection. A portable battery was used in the experiment although the acceleration sensor, data logger and the computer of the monitoring system are supposed to be powered by the battery of the bus. In the experiment, in order to investigate the influence of operating conditions such as weather, the number of oncoming vehicles, vehicle speed and the number of occupants on characteristic deflection, measurement on the bus was conducted by two persons. Of the two persons, one, seated at the back of the bus, recorded the time at which the bus passed over each bridge and the number of occupants, and the other, seated at the front of the bus, recorded the number of oncoming vehicles and bus speed.

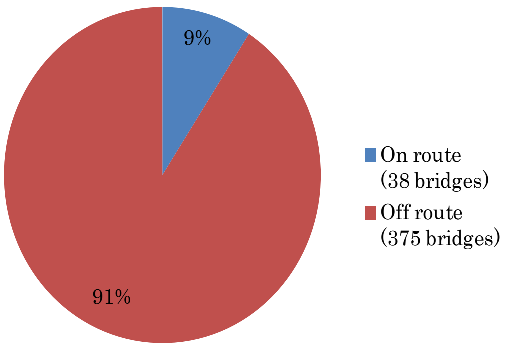


Figure 2. Percentage of bridges on Ube city bus

Table 2. Measuring conditions

Period	December 1, 2010 to November 11, 2011
Measurement period	39 days
Bus routes	Nishi Ube–Koto Line Nishigaoka–Nisseki Line Obayama Line Chuo Byoin Line
Bridges	12. Nameless bridge 33. Myojin Bridge 39. Nameless bridge 52. Miyagawa Bridge 53. Myojin Bridge 6490. Jase Bridge 6570. Shiratsuchi Daini Bridge 8609. Shingondai Bridge

Table 3. Data on some of monitored bridges

Bridge ID	Bridge name	Date completed	Type of superstructure			Span(m)	Bridge length(m)
386490	Jase Bridge	1976	Span number	Start point 1	PC slab bridge; pretensioned slab	18.0	85.0
				2	PC slab bridge; pretensioned slab	16.0	
				3	PC slab bridge; pretensioned slab	18.0	
				4	PC slab bridge; pretensioned slab	14.0	
				End point 5	PC slab bridge; pretensioned slab	19.0	
386570	Shiratsuchi Daini Bridge	1933	Span number	Start point 1	RC girder; T-girder	7.0	15.8
				End point 5	RC girder; T-girder	7.0	
388609	Shingondai Bridge	June, 1998	Girder bridge/others			22.4	23.6

Table 4. Bus and acceleration sensor specifications

(a) Bus

Item	Specifications
Net vehicle weight	8,130kg
Gross vehicle weight	11,485kg
Front/front axle weight	2,730kg
Rear/rear axle weight	5,400kg
Distance between front and rear wheels	4.4m

(b) Acceleration sensor

Item	Specifications
Acceleration sensor	Fuji Ceramics SA11ZSC-TI
Type of sensor	Piezoelectric type
Sampling rate	1000HZ

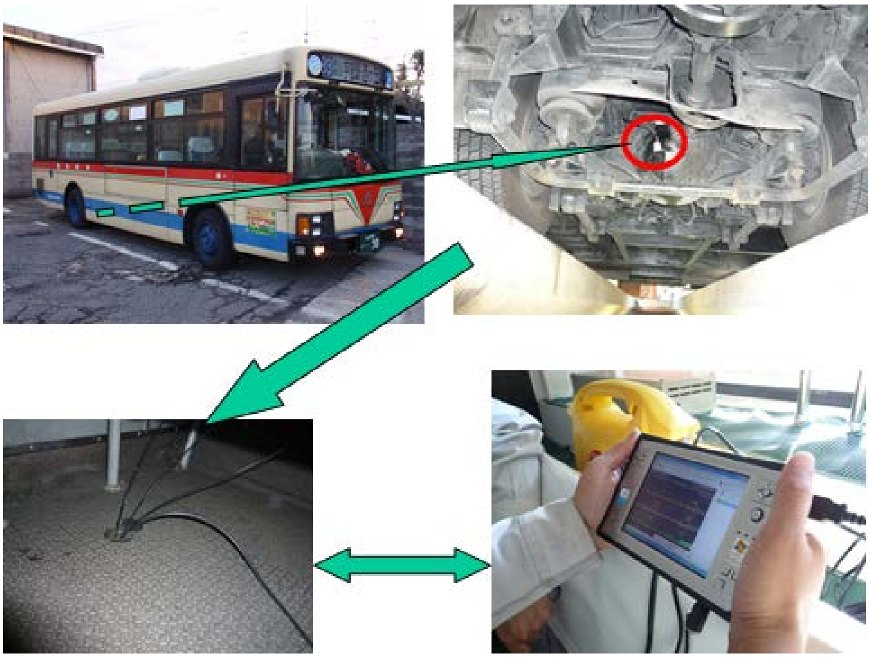


Figure 3. Measuring equipments

2.2 *Comparison of Rear-wheel-spring-of-bus Vibration and Girder Midspan Vibration*

For the purpose of determining whether or not the characteristic deflection of a bridge can be accurately extracted from the acceleration response of the rear wheel spring of the bus, an acceleration sensor was installed in the midspan region of the Shingondai Bridge, and the measurement result thus obtained was compared with the acceleration response measured under the rear wheel spring of the bus.

Fig. 4 shows the location of the waterproof acceleration sensor installed at a footway of the Shingondai Bridge and the path of the bus (bus lane). The operating conditions at the time of the measurement were as follows: weather: rainy, bus speed: 35 km, the number of oncoming vehicles: 1, and the number of occupants: 10. Fig. 5 shows the midspan acceleration response of the bridge. The graph indicates that the passing bus forced the bridge to vibrate. Fig. 6 compares the under-rear-wheel-spring acceleration response of the bus and the girder midspan acceleration response, both of which were measured when the bus passed over the bridge. As shown, the two waveforms show a fair degree of similarity although the under-rear-wheel-spring acceleration response tends to be greater. From this, it can be concluded that the vibration behavior of a bridge can be accurately extracted from the under-rear-wheel-spring vibration of

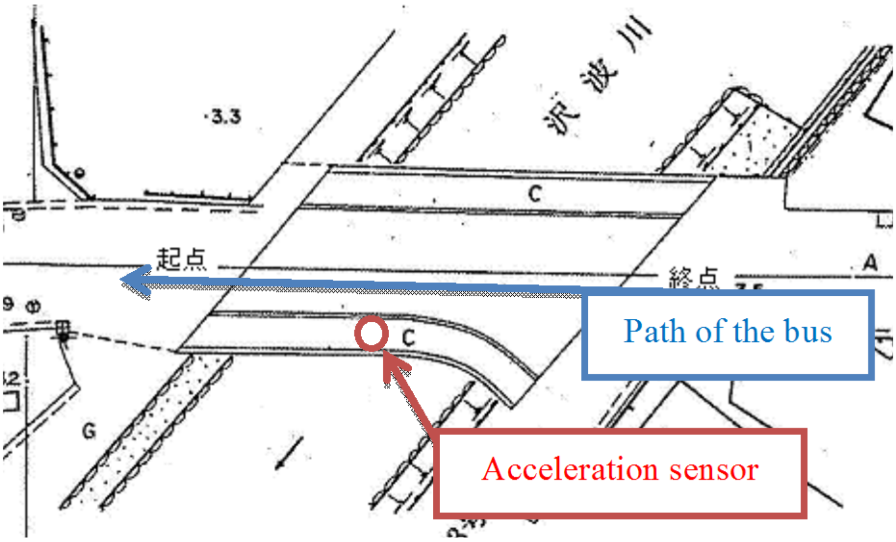


Figure 4. Acceleration sensor location on the upper surface of a bridge and the path of the bus

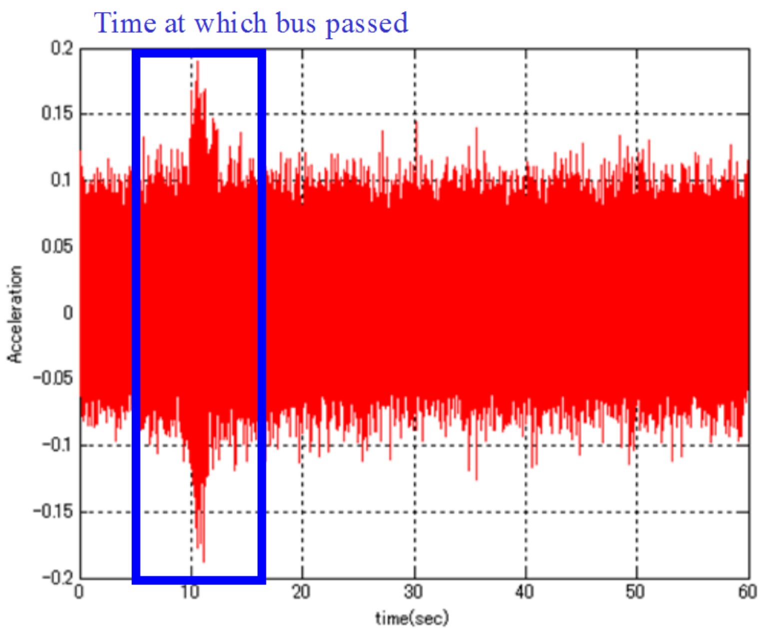


Figure 5. Example of girder midspan acceleration response

the bus. For the purpose of comparing the under-rear-wheel-spring vibration characteristics of the bus and the girder midspan vibration characteristics during the passage of the bus over the bridge, frequency slice wavelet transform (FSWT) a time–frequency analysis method(Yan(2009)), was used to analyze the two sets of acceleration response data. The FSWT analysis results for the girder midspan and under-rear-wheel-spring acceleration responses are shown in Figs. 7(a) and (b) and Figs. 8(a) and (b), respectively. As shown in Fig. 7, the passage of the bus caused midspan vibration of the bridge girder at around 12.0 Hz. The vibrations at around 44.0 Hz and 65.0 Hz shown in Fig. 7 are thought to have been caused by some kind of noise. On the other hand, as shown in Fig. 8, the rear wheel spring of the bus kept vibrating at around 12.0 Hz, regardless of the passage of the bus.

These results indicate that when the bus passed over the bridge, the rear wheel spring of the bus and the girder were vibrating together.

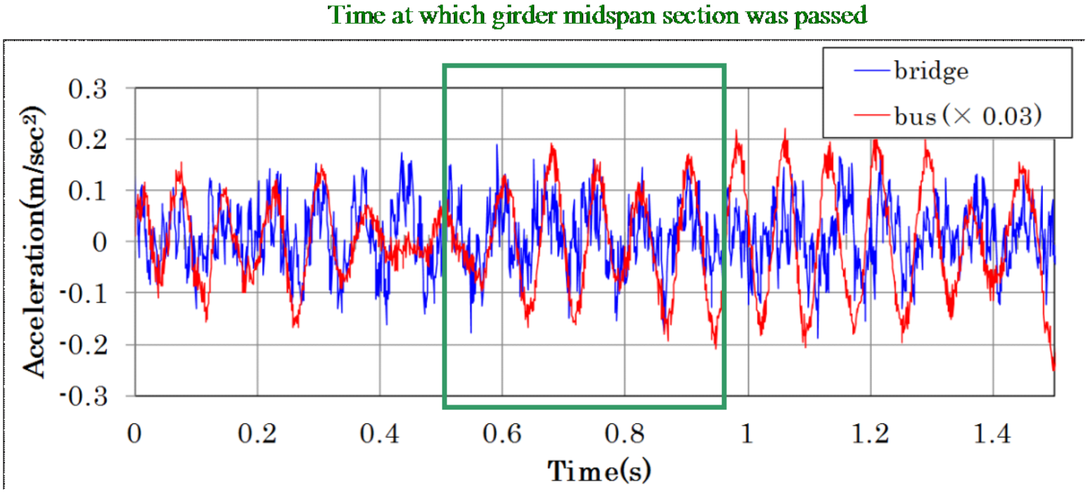


Figure 6. Comparison of under-rear-wheel-spring acceleration response and girder midspan acceleration response

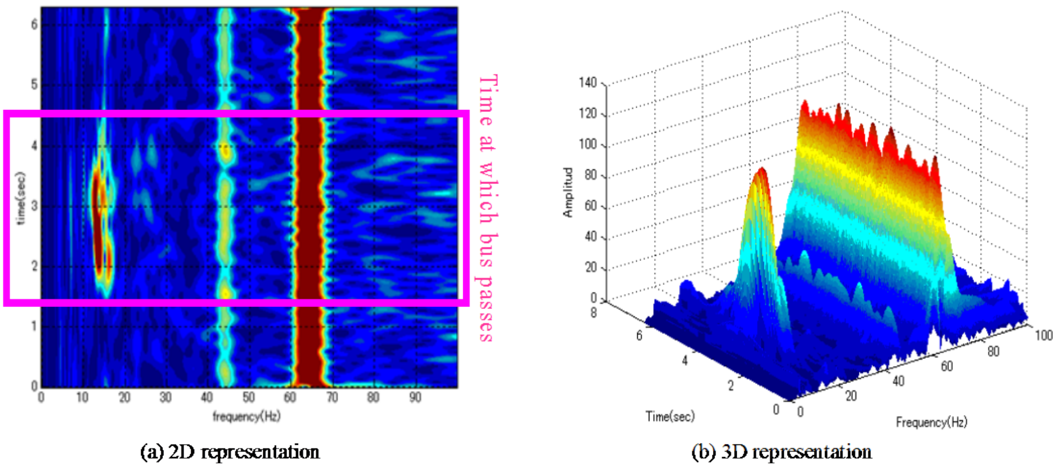
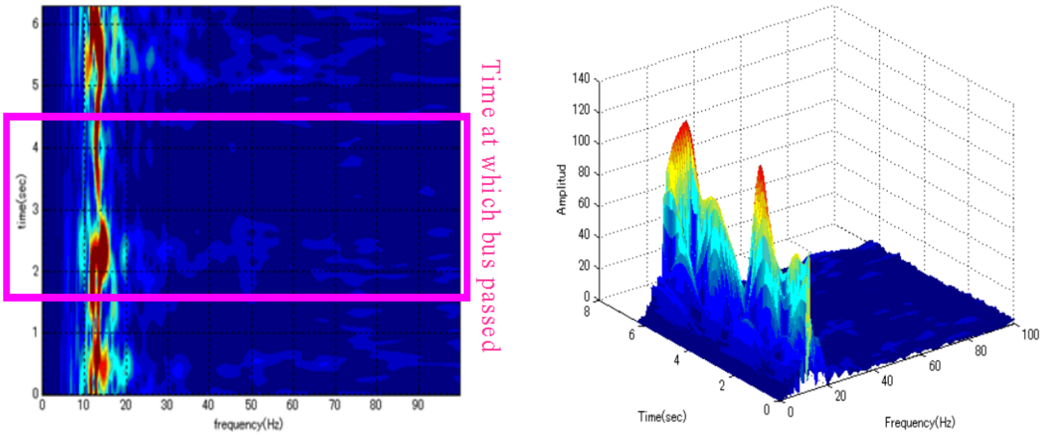


Figure 7. Results of FSWT analysis of girder midspan acceleration response before and after passing over the bridge



(a) 2D representation (b) 3D representation

Figure 8. Results of FSWT analysis of under-rear-wheel-spring acceleration response of bus before and after passing over the bridge

2.3 Discussion on Operating Conditions and Characteristic Deflection

From the results of the measurements conducted for about one year, the correlations between characteristic deflection and the operating conditions at the three bridges mentioned earlier were determined. In view of the results thus obtained, the method to be used for evaluating characteristic deflection values was determined.

2.3.1 Calculated characteristic deflections of existing bridges

In order to determine characteristic deflection, it is necessary, as the first step, to extract data obtained when the bus was passing the midspan zone of the bridge. Fig. 9 shows an example of a method of extracting such data for the Shingondai Bridge. In the case of the 23.6-meter-long Shingondai Bridge, data corresponding to an about-10-meter-long midspan section were extracted, and deflection was estimated by integrating acceleration twice. As an example, Fig. 10 shows the calculation results for characteristic deflection during the process in which the bus passed over the Shingondai Bridge in the direction from the Nishikiwa Gakkomae bus stop toward the Tokonami bus stop (N→T) (initial trip). The data extraction section was determined so that similar waveforms can be obtained from all acceleration responses. The reason why data length varies is that the bus speed was not constant during measurement.

Table 5 shows the characteristic deflections calculated by time-averaging the estimated deflections. From this, it can be inferred that although numerical values vary, calculated values can be made to converge by acquiring a large amount of data and taking averages. On the other hand, Table 6 shows the estimated deflections and characteristic deflections during the process in which the bus passed over the bridge in the direction from the Tokonami bus stop toward the Nishikiwa Gakkomae bus stop (T→N) (return trip). Comparison with Table 5 shows that even if the same bridge is involved, there are significant differences in estimated deflection waveform characteristics and characteristic deflection between the initial trip and the return trip. These variabilities are thought to be attributable to operating conditions such as weather, the number of oncoming vehicles, vehicle speed and the number of occupants.

Thus, it has been confirmed that characteristic deflection depending on bridges, spans and the direction of travel. It has also been shown that numerical values vary depending on the operating conditions. It can therefore be concluded that the important thing in calculating characteristic deflection is to always extract corresponding data from measurement data involving different bridges, different spans and different directions of travel and observe changes in the data thus extracted.

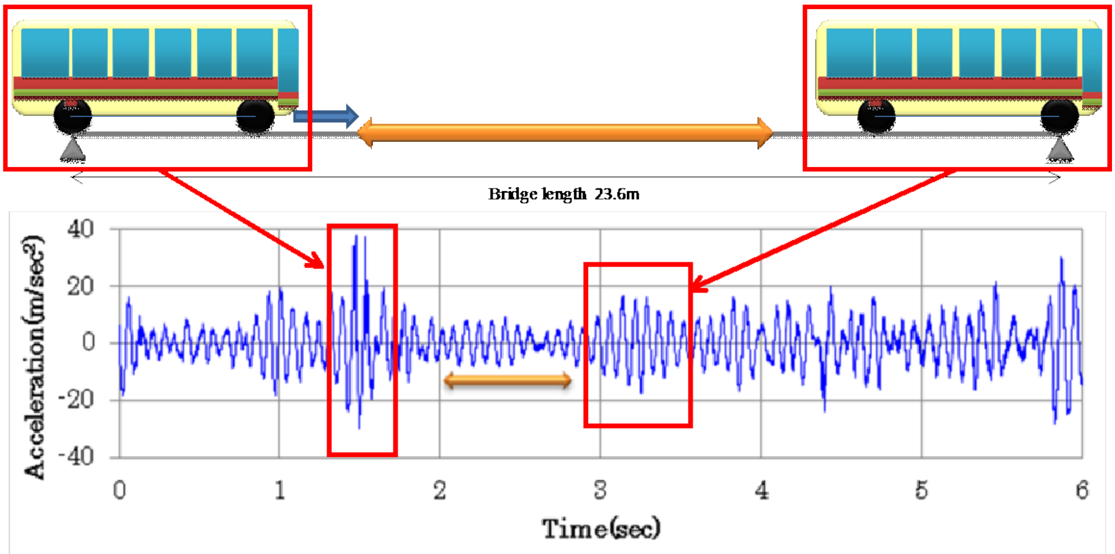


Figure 9. Example of data extraction section (Shingondai Bridge)

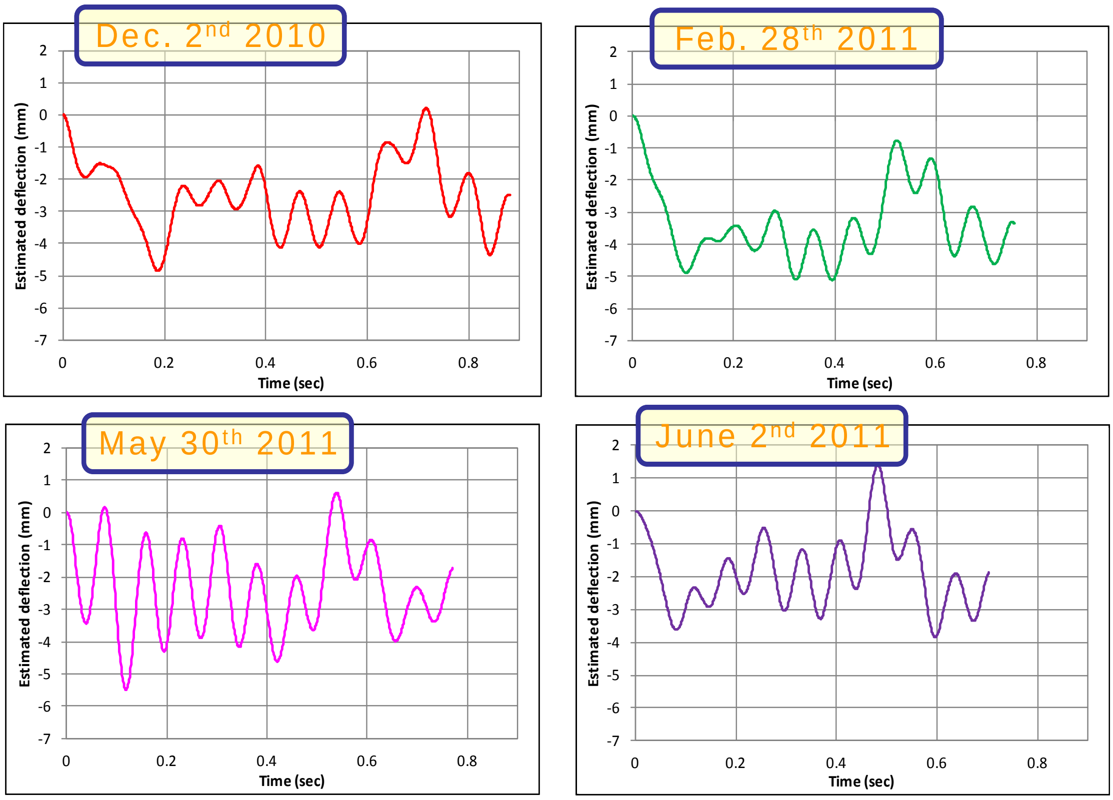


Figure 10. Example of estimated deflection from bus vibration (Shingondai bridge; N → T)

Table 5. Example of measured characteristic deflection(mm) (Shingondai bridge; N → T)

Date	Characteristic deflection	Weather	No. of oncoming vehicles	Bus speed (km/h)	No. of occupants
Dec.1, 2010	-2.13	Clear	0	45	8
Dec.2, 2010	-2.51	Cloudy	1	40	7
Feb.28, 2011	-3.36	Cloudy	1	45	6
May.30, 2011	-2.39	Clear	0	40	12
June.1, 2011	-2.07	Clear	0	45～50	9
June.2, 2011	-1.89	Clear	0	45	13

Table 6. Example of measured characteristic deflection(mm) (Shingondai bridge; T → N)

Date	Characteristic deflection	Weather	No. of oncoming vehicles	Bus speed (km/h)	No. of occupants
Dec.1, 2010	-6.99	Clear	1	45	7
Dec.2, 2010	-8.80	Clear	0	45	9
Dec.21, 2010	-5.87	Rain	1	35～40	9
Feb.28, 2011	-8.61	Cloudy	0	45	8
April.27, 2011	-4.40	Rain	1	40	6
May.11, 2011	-3.29	Light rain	0	40	10

2.3.2 Effects of bus operating conditions on characteristic deflection

In this study, the correlations between characteristic deflection and the operating conditions (disturbance factors; weather, number of oncoming vehicles, number of occupants, running speed of bus) were determined to investigate the characteristics of disturbance factors $\delta x(t)$ (Bridge Vibration Study Group(1993)) under different operating conditions. According to the correlation coefficients thus obtained, the strength of correlations was classified. As a result, concerning the effects of different operating conditions on characteristic deflection, different tendencies were obtained depending on the bridge concerned, span and the direction of travel (see Table 7). Detailed examination of individual data, however, has revealed that characteristic deflection varies to some degree regardless of operating conditions. After realizing the automation of characteristic deflection calculation, therefore, it will be necessary to reverify the influence of the operating conditions on characteristic deflection.

2.4 Method of Evaluating Characteristic Deflection

For the purposes of this study, it is assumed that disturbance factors $\delta x(t)$ have some kind of statistical properties. On this assumption, a study is conducted as to whether or not characteristic deflection converges to the extent that judgment as to the occurrence of abnormality is not affected by increasing the number of samples, N, by use of central limit theorem. In other words, the variability of characteristic deflecti on is reduced by the moving average method, and the resulting changes are observed.

2.4.1 Determination of data interval

Moving averages were calculated by varying the data interval, and standard deviations of characteristic deflections were determined. The results are shown in Fig. 11 as an example. The term "data interval" refers to the number of data sets from which moving averages are calculated. As shown, as the data interval is made larger, the variability of characteristic deflection values decreases. It can further be seen that after data interval exceeds a certain limit, the standard deviation no longer changes. This means that variability is reduced by averaging characteristic deflections, irrespective of bridges, spans or the direction of travel. In this study, changes in characteristic deflection are evaluated in terms of moving average by using a data interval of 14.

Table 7. Summary of Correlations between Characteristic Deflection and Operating Conditions

Bridge name	Span	Moving direction	Weather	No. of oncoming vehicles	No. of occupants	Bus speed
Jase Bridge	A	K → S	–	Little correlation	Little correlation	Moderate positive correlation
	B		–	Little correlation	Little correlation	Little correlation
	C		–	–	Little correlation	Weak negative correlation
	D		–	Weak negative correlation	Little correlation	Weak positive correlation
	E		–	–	Little correlation	Little correlation
	A	S → K	–	–	Little correlation	Little correlation
	B		Little correlation	Little correlation	Little correlation	Little correlation
	C		Little correlation	Little correlation	Little correlation	–
	D		Moderate negative correlation	Little correlation	Weak negative correlation	Weak negative correlation
	E		Weak negative correlation	Little correlation	Little correlation	Weak positive correlation
Shingondai Bridge	–	T → N	–	Weak positive correlation	Little correlation	Little correlation
	–	N → T	–	Weak negative correlation	Little correlation	Moderate positive correlation
Shiratsuchi Daini Bridge	A	N → Y	–	–	Weak negative correlation	Moderate negative correlation
	B		–	Little correlation	Moderate positive correlation	Weak negative correlation
	A	Y → N	–	Strong negative correlation	Weak negative correlation	Little correlation
	B		–	–	Little correlation	Little correlation

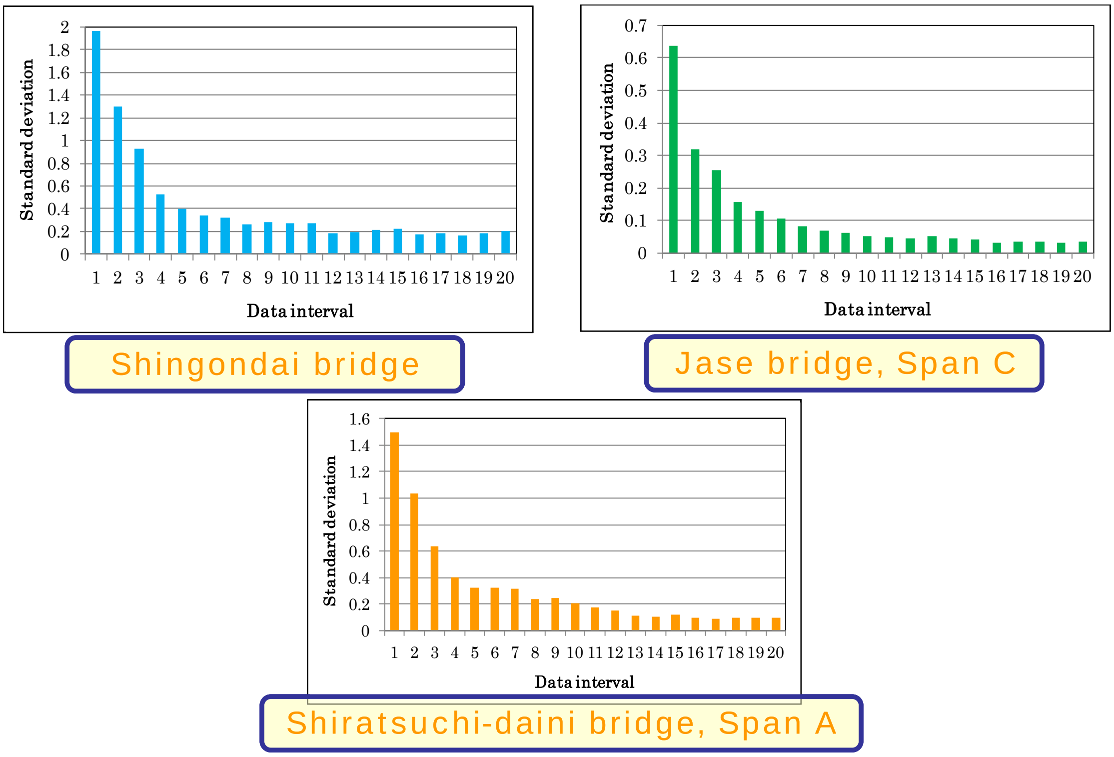


Figure 11. Changes in standard deviation depending on data interval (Data management)

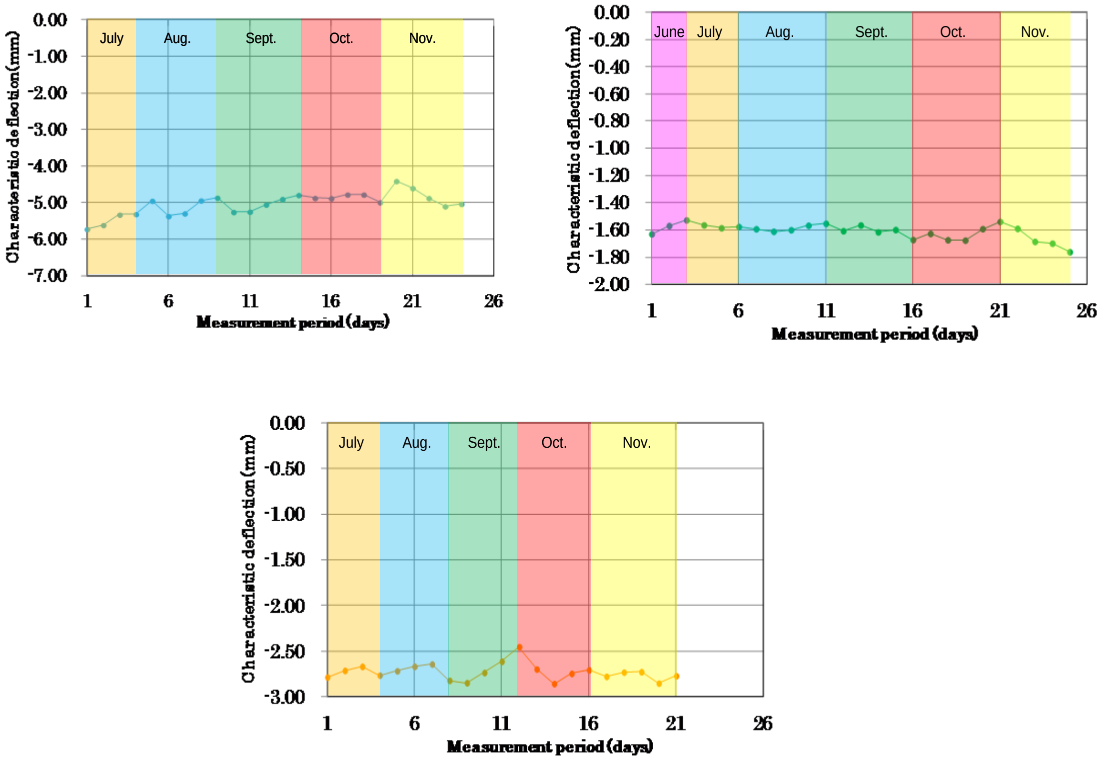


Figure 12. Examples of Season's Change of Characteristic Deflection

2.4.2 Changes in characteristic deflection of each bridge

Fig. 12 shows some examples of changes in characteristic deflection of different bridges expressed in terms of moving averages by using a data interval of 14. As shown, characteristic deflection increases and decreases because measurements vary. Thus, it is possible to propose a method for monitoring bridge deterioration over time by continuously measuring characteristic deflection. The next chapter describes how to determine evaluation criteria.

3 CONCLUSIONS

This paper introduced on the results of the experiment carried out for the validation of a bridge monitoring system using an in-service fixed-route bus (Miyamoto & Yabe(2012)) over a period of one year from December, 2010. Main findings of this study are summarized below:

1) It has been confirmed that when the bus passed over a bridge, the midspan region of the bridge was forced to vibrate. It has been found that the under-rear-wheel-spring section of the bus and the midspan region of the bridge vibrated at the same frequencies. The deflection characteristics of the bridge, therefore, can be estimated from the under-rear-wheel-spring acceleration response of the bus during its passage over the bridge.

2) It has been confirmed that characteristic deflection varies depending on bridges, spans and the direction of bus movement. It has also been found that characteristic deflection also varies depending on the operating conditions. It can be concluded, therefore, that what is important in calculating characteristic deflection is to always extract exactly corresponding data from measurement data involving different bridges, different spans and different directions of travel and carefully observe their changes.

3) In order to identify the characteristics of disturbance factors $\delta x(t)$ under the bus operating conditions, correlations between characteristic deflection and the operating conditions were investigated. As a result, the influence of the operating conditions on characteristic deflection showed different tendencies bridges, spans and the direction of travel. Examination of each set of data revealed that characteristic deflection varies to some degree regardless of the operating conditions.

4) Since the variability of characteristic deflection increases depending on disturbance factors attributable to differences in operating conditions and differences in data extraction and processing methods, methods for reducing variability by assuming statistical properties were studied. As a result, it has been confirmed that calculated values can be made to converge to the extent that abnormality evaluation results are not affected by making sure that the number of samples, N, is greater than a certain limit. This means that the variability of characteristic deflection can be reduced by the moving average method with varied time intervals, and its rate of change, α, can be used as a structural abnormality parameter.

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