ONE YEAR VIBRATION MONITORING OF A SHORT SPAN BRIDGE UNDER IN SERVICE ENVIRONMENTS

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This study investigates effects of temperature and traffic on structural health monitoring of a short span bridge using the vibration data measured through a year. Acceleration, strain and temperature of the bridge are measured in the monitoring. The traffic pattern is estimated using the strain responses of bridge decks, which forms a part of bridge-weigh-in-motion. Coefficients of the auto-regressive model of the signal taken from the bridge are used as a parameter for bridge diagnosis. This study also examines the feasibility of approximating functional relationships between identified parameter and temperature by a simple linear regression model.

Hypothesis test for correlation demonstrates correlation between the damage-sensitive feature and temperature. On the other hand weak correlation between the damage-sensitive feature and total mass of traffic is observed. However, it is noteworthy that the dynamic effect from traffic should be considered to derive a reliable result on the effect of traffic to the identified parameter except the traffic mass effect. The parameter identified from acceleration signals when a heavy truck collides with a concrete barrier of the bridge were successfully recognized as an abnormal signal using a fault detection using a statistical criterion. It demonstrates feasibility of the proposed approach in BHM.

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ABSTRACT: This study investigates effects of temperature and traffic on structural health monitoring of a short span bridge using the vibration data measured through a year. Acceleration, strain and temperature of the bridge are measured in the monitoring. The traffic pattern is estimated using the strain responses of bridge decks, which forms a part of bridge-weigh-in-motion. Coefficients of the auto-regressive model of the signal taken from the bridge are used as a parameter for bridge diagnosis. Feasibility of the fault detection using a statistical criterion is examined.

1 INTRODUCTION

A strong motivation behind the bridge health monitoring (BHM) using vibration measurements is that the change of structural integrity of bridges alters system parameters and information about changes of system parameters of the bridge remains in the monitored vibration data. Many techniques to identify the hidden information of structural integrity in the vibration data are proposed to diagnose damages in bridge structures, and are successfully applied to the structures in controlled environments such as laboratories. Considering application to real structures, on the other hand, a crucial issue is that environmental effects also lurk in the measured vibration data since the variability in dynamic properties can be a result of time-varying environmental and operational conditions (e.g. Peeters and De Roeck (2000), Sohn et al. (2003)). In making a decision for diagnosis of bridges, how to separate or consider these in-service environments from signals of bridges' dynamic responses is an important technical issue.

As in-service effects on vibration monitoring of bridges, temperature, wind-induced and traffic-induced vibrations and traffic mass effects are factors to be considered. Focusing on short span bridges, however, temperature and traffics are dominant factors affecting the vibration of bridges. Temperature variation can change stiffness of asphalt pavement (Lukanen et al. (2000)) as well as boundary condition of the bridge (Namatame et al. (2009)). Considering bridge-vehicle interactive system traffic mass can raise total mass of the system, and results variation of identified system frequencies. The dynamic effect of vehicles on the bridge also influences to the system's vibration (Kim et al. (2005)).

This study investigates effects of temperature and traffic on structural health monitoring of a short span bridge using the vibration data measured through a year. During the vibration monitoring, temperature of bridge surface is measured. Traffic pattern is observed using a bridge-weigh-in-motion (BWIM) system. Acceleration signals observed when a heavy truck collides with a concrete barrier of the bridge are used to examine feasibility of the fault detection using a statistical criterion.

Coefficients of an auto-regressive model (AR coefficient) of signals obtained from the bridge are the observed parameter. This study also tries to normalize the effect of in-service environments on the parameter: i.e. functional relationships between identified parameter and temperature by a linear regression model.

2 SUMMARY FOR VIBRATION MONITORING

The seven-span plate-Gerber bridge shown in Figure 1 is the observation bridge which is located on a busy route of Japanese national roads. Table 1 shows a brief summary of the bridge. The monitoring covers measuring strains of RC decks, accelerations of steel girders and RC decks and temperature of the bridge. Details of the sensor deployment are also summarized in Figure 1. Therein, US and DS denote strain gauges to measure strain signals of deck slabs on up and down lanes respectively. UG and DG denote those strain gauges to measure girders' strain signals which are used for identifying traffics in terms of BWIM. UA and DA stand for accelerometers to measure acceleration responses of girders respectively on up and down lanes. Thermometers are denoted by T. The sampling rate is 200Hz for acceleration and strain measurements. Temperature is measured once every hour.

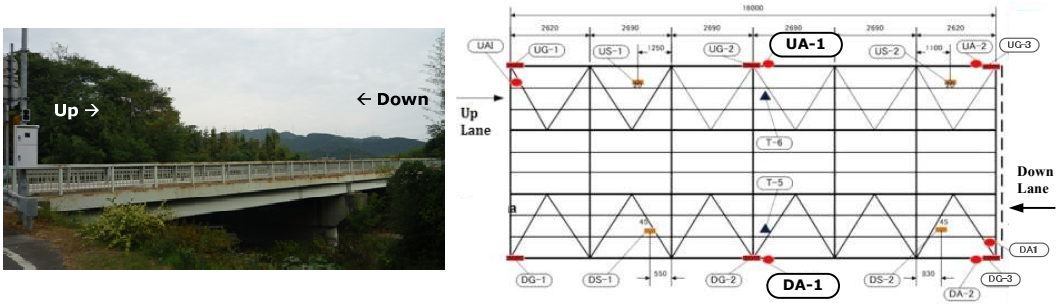


Figure 1. Photo, plan view and sensor deployment of observation bridge.

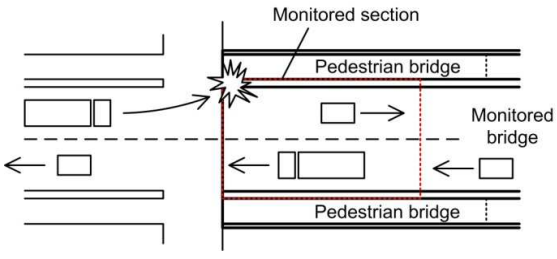


Figure 2. Situation of traffic accident.

Table 1. Properties of observation bridge.

Construction year		1960
Bridge length (m)		187.0
Span length (m)	Hanging girder	16.0
	Anchorage girder	6.2+28.4+6.2
Width (m)		8.0

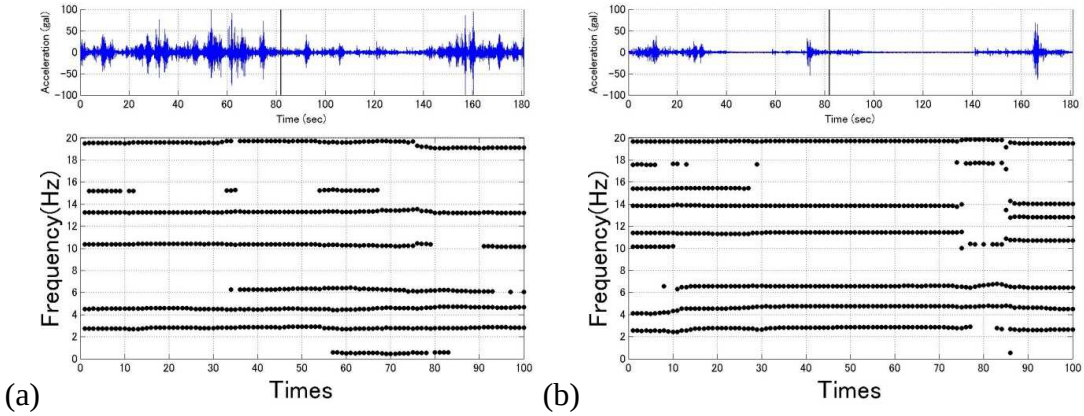


Figure 3. Measured acceleration responses of the observation bridge at UA-1 and identified system frequencies by AR model: (a) Wednesday 7:00 AM; and (b) Sunday 7:00 AM.

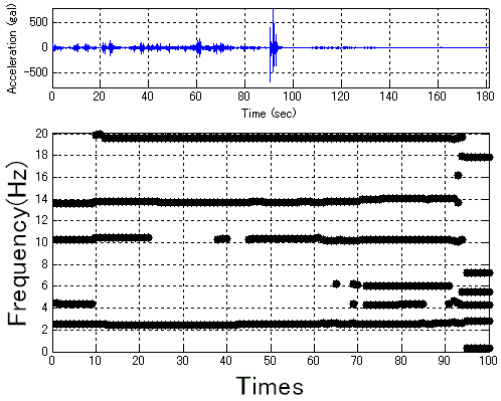


Figure 4. Measured acceleration response of the observation bridge at UA-1 and identified system frequencies by AR model before and after colliding with a heavy truck.

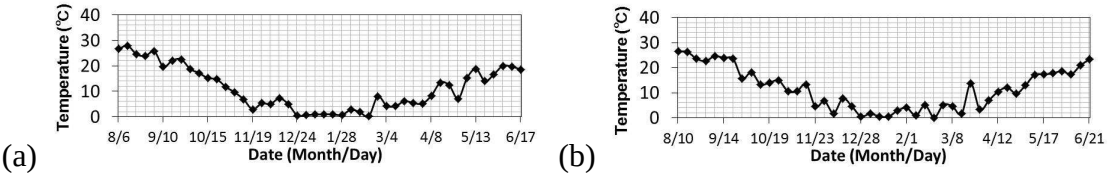


Figure 5. Variation of bridge temperature: (a) every Wednesday 7:00AM; and (b) every Sunday 7:00AM.

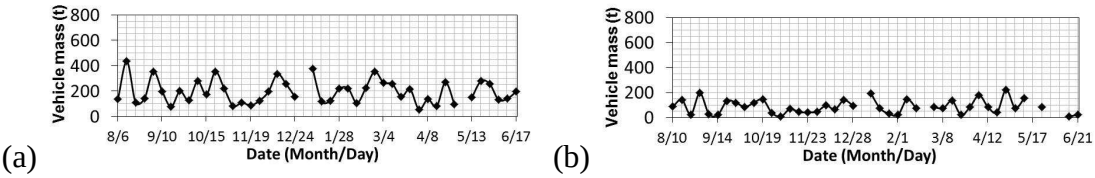


Figure 6. Variation of total mass of traffic traveling on bridge during observation time of 180 seconds: (a) every Wednesday 7:00AM; and (b) every Sunday 7:00AM.

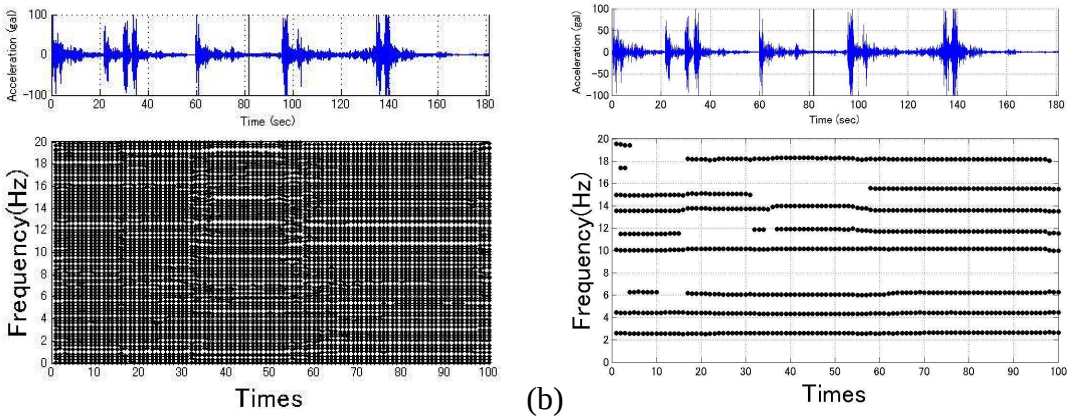


Figure 7. Identified system frequencies: (a) from an optimal AR model; (b) from an arbitrarily decided AR model.

A noteworthy point is that during the monitoring a car crash, which a heavy truck collides with a concrete barrier of the bridge as shown in Figure 2, has occurred. However no structural damage on main girders due to the car crash is reported. Signals observed at the time of the car crash are assumed as data of the bridge under an abnormal condition.

This study focuses on acceleration responses at observation points UA-1 and DA-1. 36184 samples of those data measured at 7:00 AM and 4:00 PM on every Wednesday and Sunday are examined. The acceleration response observed at UA-1 on a Wednesday morning 7:00 is shown in Figure 3(a), and identified frequencies by assuming signals to follow the autoregressive process are appeared below the acceleration time history. Figure 3(b) shows the signals observed on Sunday 7:00 AM. The time history observed on Wednesday 7:00 AM apparently comprises more peaks than those on Sunday 7:00 AM. It demonstrates that number of vehicles travel on Wednesday is greater than that on Sunday. The acceleration response at the time of the car crash is shown in Figure 4 in which peak responses around 90s indicate the acceleration at the time of the car crash.

Variations of temperature and vehicle mass on Wednesday and Sunday 7:00 AM are shown in Figure 5 and Figure 6, respectively. Figure 5 shows that the change of temperature through one year is about 30 degrees Celsius. The total mass of traffic traveling on the bridge during observation time about 180 seconds again demonstrates heavier traffics (or traffic volume) on Wednesday than on Sunday as shown in Figure 6.

3 VIBRATION DIAGNOSTIC INDICATOR

Bridge health monitoring based-on ambient vibration measurements has been focusing on variation of modal parameters of bridge structures such as modal frequencies, modal damping and mode shapes. Considering BHM for short span bridges, the major source of bridge vibrations comes from interaction between traveling vehicles and the bridge, so called traffic-induced vibration of bridges. Therefore the system parameter identified from the traffic-induced vibrations of short span bridges is bridge-vehicle interactive system's parameters rather than modal parameter of the bridge because signals obtained in-service environments of short span bridges are not the responses of the observation bridge itself but those of the bridge-vehicle interactive system (Kim et al. (2010)).

Identifying the system parameter from vibration data by means of linear time-series models such as autoregressive (AR) model is a promising approach. Those system parameters of bridge structures, however, are sometimes insensitive to damage, or easily affected by noises. Another problem in identifying system frequency and damping constant estimated from the time series model is how to decide the optimal order of the time series model. Of course there are methods to determine the optimal order of a time series model, e.g. Akaike Information Criteria (AIC) (Gersh et al. (1973)). However the optimal time series model for vibration responses of bridge structures usually comprises a higher order term. As a result the optimal model even detects numerical parameters, and causes false system frequencies and damping constants. Figure 7 (a) shows identified system frequencies with false system frequencies by an optimal AR model. These false system frequencies and damping constants make it difficult to choose proper parameters affected by structural damages. Comparing with those taken from the optimal AR mode, the AR model with the artificially decided AR order shown in Figure 7(b) provides better chance to decide the system frequencies. To overcome the shortcomings, this study adopts a parameter from coefficients of an optimal AR model for abnormality detection of bridges instead of focusing on system frequency and damping constant since linear dynamic systems can be idealized using the AR model shown in Eq.(1) (He and De Roeck (1997), Kim et al. (2010)).

$$y(k) = \sum_{i=1}^{p} a_i y(k-i) + e(k) \tag{1}$$

where, $y(k)$ denotes output of a system, a_i is the i-th order AR coefficient and $e(k)$ indicates an error term.

The parameter from AR coefficients defined by Eq. (2) is adopted as a Damage-Sensitive Feature (DSF) (Nair et al. 2006).

$$DSF = \frac{|a_1|}{\sqrt{a_1^2 + a_2^2 + a_3^2}} \tag{2}$$

where, a_1, a_2 and a_3 are the first three AR coefficients.

Nair et al. (2006) reports that the DSF depending on the AR coefficients is the most promising because these coefficients are statistically the most significant among all the coefficients of model. The first and fourth authors of this paper also already examined that the DSF considering up to the third order of AR coefficients is a promising parameter in BHM since the most clear change of DSF due to damage is observed through a bridge-moving vehicle laboratory experiment (Kim et al. (2011)). Therefore this study adopts the DSF by Nair et al. without doing any further sensitivity analysis about the effect of order of AR coefficient. In this study, however, residual defined as Eq. (3) is used as a parameter for diagnosis of bridges.

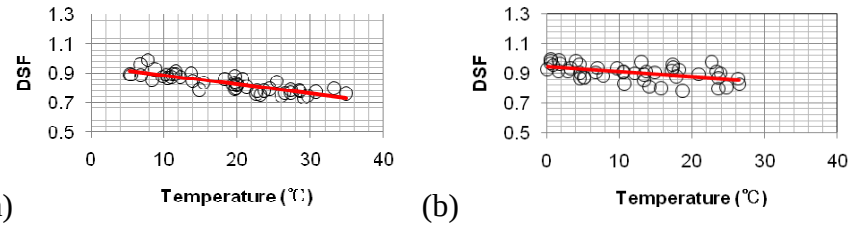
$$\varepsilon = DSF - DSF_{LRG} \tag{3}$$

where DSF denotes the observed damage-sensitive feature. DSF_{LRG} stands for a simple linear regression model between DSF and vehicle mass or temperature fluctuation. Equation (4) shows a simple linear regression model for temperature fluctuation. Therein, a denotes a linear coefficient and b is a disturbance term. T denotes temperature.

$$DSF_{LRG} = aT + b \tag{4}$$

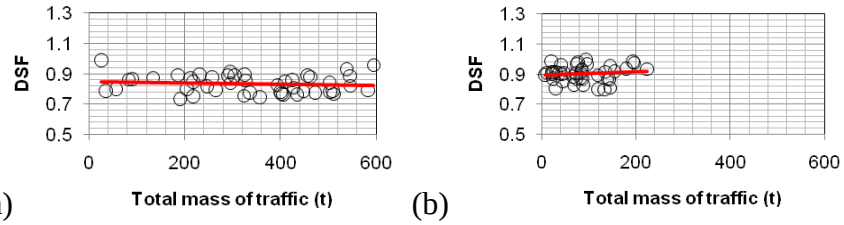
It is noteworthy that in considering thermal dynamics of bridges the linear regression model does not guarantee proper approximation. However, no clear phase of temperature with respect to measurement location of the observation bridge is observed especially in the transverse direction. Therefore, this study tries to use the simple linear regression model.

In order to detect change of bridge's health condition, this study adopts 95 per cent confidence interval of the residual as a damage indicator. The 95 per cent confidence interval means that the interval contains 95 per cent of the residuals of signals taken from the intact state of bridges. Therefore, it is possible to make a decision on the health condition of the bridge by measuring how much the newly observed residuals deviate from the confidence interval.



(a) (b)

Figure 8. DSF vs. Temperature: (a) Wednesday 4:00 PM; and (b) Sunday 7:00 AM.



(a) (b)

Figure 9. DSF vs. total mass of traffic: (a) Wednesday 4:00 PM; and (b) Sunday 7:00 AM.

Table 2. Correlation between DSF and temperature of observation point UA-1.

	Wednesday		Sunday	
	7:00 AM	4:00 PM	7:00 AM	4:00 PM
Coefficient of Correlation	-0.631	-0.841	-0.516	-0.580
test statistic (t_0)	5.39	10.3	4.00	4.72
Significance level	0.05	0.05	0.05	0.05
rejection region	$\|2.01\| < t_0$	$\|2.01\| < t_0$	$\|2.01\| < t_0$	$\|2.01\| < t_0$
reject	○	○	○	○
result	**H_1**	**H_1**	**H_1**	**H_1**

Table 3. Correlation between DSF and total mass of traffic of observation point UA-1.

	Wednesday		Sunday	
	7:00 AM	4:00 PM	7:00 AM	4:00 PM
Coefficient of Correlation	-0.0429	-0.114	0.104	-0.0113

test statistic (t_0)	0.278	0.760	0.653	0.0732
Significance level	0.05	0.05	0.05	0.05
rejection region	$\|2.01\| > t_0$	$\|2.01\| > t_0$	$\|2.01\| > t_0$	$\|2.01\| > t_0$
reject	×	×	×	×
result	**H_0**	**H_0**	**H_0**	**H_0**

4 FEASIBILITY INVESTIGATION

4.1 Damage-sensitive feature versus temperature

The correlation between estimated DSFs and temperatures is firstly invesitgated by means of the hypothesis test for correlation. Plots between DSFs and temperatures on every Wednesday 4:00 PM and Sunday 7:00 AM are shown in Figure 8 which shows tendency of decreasing DSF with rising temperature. Results of the hypothesis test for the data observed at UA-1 are summarized in Table 2 in which H_0 denotes the null hypothesis meaning true correlation is equal to 0 and H_1 is the alternate hypotheses meaning that true correlation is not equal to 0. It is clear from the hypothesis test for correlation that there are correlation between DSF and temperature.

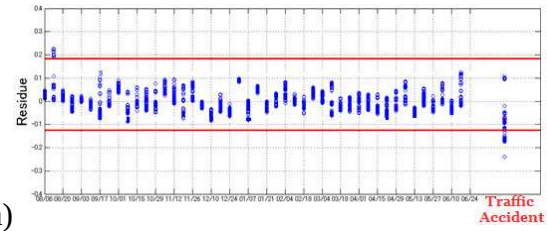
4.2 Damage-sensitive feature versus total mass of traffic

The correlation between estimated DSF and total mass of vehicles is also invesitgated by means of the hypothesis test for correlation. Plots between DSF and total mass of vehicles on every Wednesday 4:00 PM and Sunday 7:00 AM are shown in Figure 9. It is haqrd to find a correlation between DSF and total mass of vehicles. Hypothesis test results also demonstrates a weak correlation between DSF and total mass of traffic as shown in Table 3.

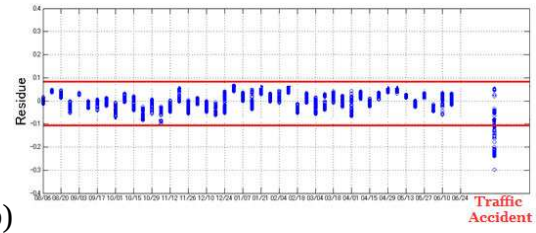
4.3 Feasibility of bridge diagnosis using damage indicator

According to the previously discussed correlation between damage-sensitive feature and in-service environments, a simple linear regression model between DSF and temperature fluctuation is firstly identified, and then the residual is estimated according to Eq.(3).

Those residuals during the monitoring period are plotted with 95 per cent confidence interval as shown in Figures 10 and 11. Observations show that the residuals taken from the signal of traffic accident apparently deviate from the confidence interval. It demonstrates feasibility of BHM by means of the proposed approach.

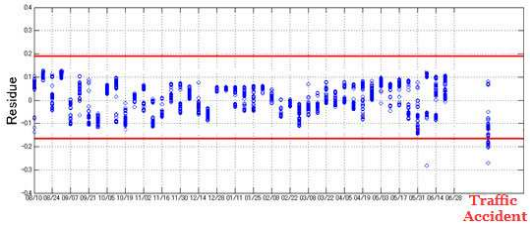


(a)

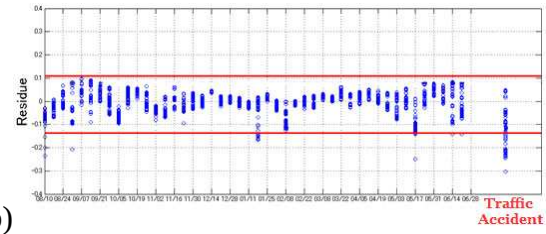


(b)

Figure. 10 Residual with 95.4% confidence interval on Wednesday 4:00 PM: (a) UA-1; and (b) DA-1.



(a)



(b)

Figure. 11 Residual with 95.4% confidence interval on Sunday 7:00AM: (a) UA-1; and (b) DA-1.

5 CONCLUSIONS

This study investigates effects of variations of temperature and mass of traffic as in-service environments on diagnosis of a short span bridge using the vibration data measured through a year. This study also investigates the feasibility of using AR coefficients as a parameter and confidence interval as a damage indicator to detect change of bridges' health condition.

The hypothesis test for correlation demonstrates correlation between DSF and temperature. On the other hand weak correlation between DSF and total mass of traffic was observed. The parameter identified from acceleration signals when a heavy truck collides with a concrete barrier of the bridge were successfully recognized as an abnormal signal using a fault detection using a statistical criterion. It demonstrates feasibility of the proposed approach in BHM.

Next step for this study is to investigate how to make a decision on diagnosis of bridges qualitatively. For traffic effect, it makes sense to monitoring bridges neglecting the

effect of traffics considering costs of applying BWIM system to every short span bridge. However, it is worth to clarify the effect of traffics not only about traffic mass but also about dynamic effects from traffics, which is also a task to be solved.

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