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Hasegawa, Soichiro ...[et al]. Bridge damage detection using probability distribution of RMSE values of moving vehicle acceleration. Proceedings of the 20th working conference of the IFIP WG 7.5 on Reliability and Optimization of Structural Systems 2022: 1-8: 1.

ISSUE DATE:
2022-09

URL:
https://doi.org/10.14989/ifipwg75_2022_1

IFIP WG7.5 working group conference
19-21 September 2022, Kyoto University, JAPAN

Bridge damage detection using probability distribution of RMSE values of moving vehicle acceleration

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ABSTRACT: In recent years, indirect bridge health monitoring methods using sensors mounted on measuring vehicles, known as drive-by methods, have received increasing attention. This study intends to investigate the feasibility of a drive-by bridge health monitoring method utilizing moving vehicle accelerations. The proposed method investigates whether there is any abnormality in the bridge by using the subtraction between the preliminary-measured vehicle acceleration when the bridge is healthy and the newly-measured vehicle acceleration when the bridge is tested. A band pass filter is applied to the vehicle accelerations before the subtraction in order to eliminate undesirable vibration components other than the frequency of the first bending mode of the bridge. The damage existence and level are investigated by calculating the RMS of the difference between the preliminary-measured and newly-measured accelerations of the vehicle. Considering the variation in the measurements, several measurements are conducted, and the RMS (Root Means Square) values and their probability distributions are examined. The laboratory experiment using a test vehicle equipped with accelerometers was conducted. Observations through this study demonstrated that the proposed method successfully determined the bridge damage existence and its level in a certain accuracy when the frequency of the first mode of the bridge varies with the damage of the bridge.

1. INTRODUCTION

Appropriate maintenance of bridges is getting more important with the increase in traffic volume and vehicle weights in recent years. A number of structural health monitoring (SHM) methods for bridges are developed and researched. Conventional bridge SHM is visual inspection, which is time-consuming and inefficient. To cope with the defect in visual inspection, a vibration-based bridge SHM has been developed, which aims to extract structural information from bridge acceleration measured on the target bridge. Such a vibration-based method is called the direct method. While the direct method has enough high accuracy, it is still time- and labor-consuming since many sensors should be installed on the target bridge.

To overcome the defect of the direct method, drive-by-bridge SHM methods (Kim & Kawatani 2009, Kim et.al. 2014, O'Brien et. al. 2014), the so-called indirect methods of bridge SHM, have been studied in recent years. The drive-by-bridge SHM indicates a bridge SHM method using vehicle vibrations during the vehicle traveling on the target bridge. For example, Yang et al. proposed a drive-by-bridge SHM method of extracting the bridge's natural frequency using vehicle vibration (Yang et.al. 2004), and Lin and Yang (2005) showed the feasibility of this method through a field experiment. Many drive-by-bridge SHM methods focus on the identification of dynamic parameters such as natural frequency (Tan et.al. 2017, Nagayama et.al. 2017), mode shape (Yang et.al. 2014, Tan et.al. 2021, Malekjafarian & O'Brien 2014), and damping (Gonzalez et.al. 2012, Keenahan et.al 2014) of the target bridge. However, the drive-by-bridge

SHM is still in the research phase and there are many challenges to practical implementation. One of the challenges in the drive-by bridge SHM is how to obtain accurate bridge information from the vehicle acceleration which originates from interacted vibration between a bridge and vehicles. The road surface roughness also affects the accuracy of the drive-by-bridge SHM.

This study proposes a method for detecting bridge anomalies using the difference between the reference vehicle acceleration measured when the target bridge is assumed to be in a healthy state, and the test accelerations measured again when the bridge is in an unknown state. A band-pass filter (BPF) is applied to the vehicle accelerations before estimating acceleration difference so that they pass only around the first-order natural frequencies of the bridge. This is to improve the accuracy of damage detection by removing vibration components other than those originating from the bridge. The proposed method does not focus on any dynamic parameters, hence is less challenging than identifying specific dynamic components in terms of screening the condition of the bridge, and thus has greater potential for practical application. The effectiveness of the proposed drive-by-bridge SHM, which focuses on anomaly detection, is verified through laboratory experiments using a model bridge with accelerometers and a model vehicle.

2. DAMAGE DETECTION THEORY

Reference vehicle accelerations are measured, and the bridge condition at that time is assumed as a healthy or reference state. For bridge damage detection, the vehicle acceleration is measured again when the test vehicle traveling on the inspection bridge. This acceleration is named test acceleration and is compared with the reference acceleration. Acceleration in the bounce direction, which is calculated from two accelerations measured on the front and rear axles, is used for damage detection. The difference between the test acceleration and reference acceleration in the time domain is estimated, and the root mean square (RMS) of the difference in the vehicle accelerations is adopted as a damage-sensitive feature. Before the difference is determined, a bandpass filter (BPF) is applied to both reference and test accelerations to remove undesirable vibration components and increase the possibility of bridge damage detection. The bandwidth of the filter is decided so that it passes only around the natural frequencies of the first bending mode of the bridge. To reduce damage detection errors due to measurement variations, multiple measurements should be performed in both the reference and test state.

The procedure of damage detection using the time histories of the vehicle accelerations is summarized as presented below.

. REFERENCE STEP

1. The vehicle accelerations while running through the target bridge are measured for N times.
2. The BPF around the first bending frequency of the bridge is applied to the accelerations.
3. The average of the bandpass filtered accelerations of the N times measurements is calculated.

. TEST STEP

1. The vehicle accelerations while running through the target bridge are measured for N times.
2. The BPF around the first bending frequency of the bridge is applied to the accelerations.
3. Differences between filtered test accelerations and the average of the reference accelerations are estimated.
4. RMS values of the differences are calculated.
5. The likelihood of bridge damage being present is examined statistically using the RMS values.

3. FEASIBILITY INVESTIGATION BY LABORATORY EXPERIMENT

3.1. *Experimental setup*

To evaluate the feasibility of the proposed method, a laboratory experiment was conducted. The steel model bridge had 5.4 m span length. A picture of the bridge is displayed in Fig. 1. The model bridge properties are presented in Table 1. The bridge has three slits at 3.14 m, 3.49 m, and 3.82 m from the exit to reduce the flexural rigidity of the bridge, as shown in Fig. 2. These slits can be reinforced as shown in Fig. 3. By utilizing this reinforcement, four levels of bridge damage status are defined. The scenario in which all slits are reinforced is assumed to the No damage scenario. The scenario in which two of three slits are reinforced is the Damage 1 scenario. The scenario in which one of three slits is reinforced is the Damage 2 scenario. Finally, the scenario in which all slits are open is the Damage 3 scenario. All scenarios are presented in Fig. 4. For the test measurements, 10 runs are conducted for each scenario of No damage, Damage 1, Damage 2, and Damage 3. In addition to that, 10 runs for the reference measurement are conducted for only No damage scenario.

The model vehicle used for the laboratory experiment is depicted in Fig. 5, and the model vehicle properties are presented in Table 2. Damping constants and spring stiffness of the model vehicle are estimated from a free vibration test. Accelerometers are located at the front and rear axles of the model vehicle. For bridge damage detection, the bounce acceleration at the center of gravity of the vehicle body is calculated by the two measured accelerations and used as input.

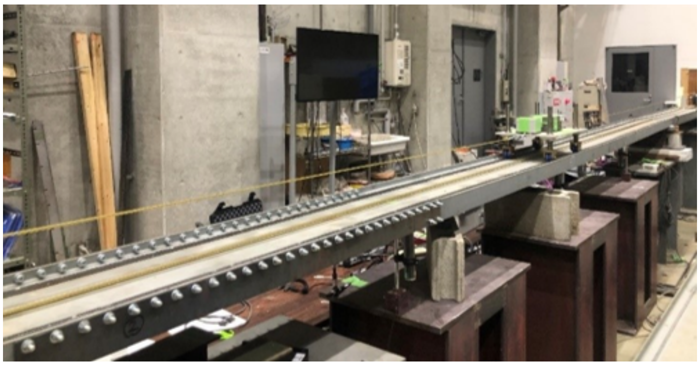

Fig. 1. Bridge used for the laboratory experiment.

Table 1 Bridge properties in the experiment

Property		Value
Span length		18000 kg
Mass per unit length		46.9 kg/m
Second moment of area		5.5×10^{7} m^{4}
Young's modulus		2.1×10^{11} N/m^{2}
First natural frequency	No damage	2.81 Hz
	Damage1	2.71 Hz
	Damage2	2.59 Hz
	Damage3	2.59 Hz

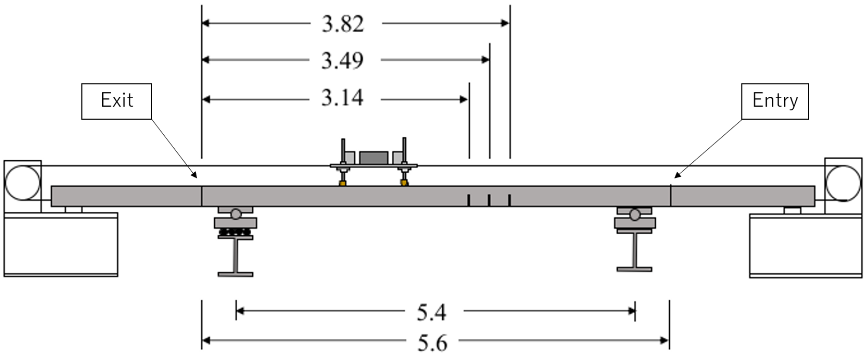

Fig. 2. Bridge scheme in laboratory experiment. (unit: m)

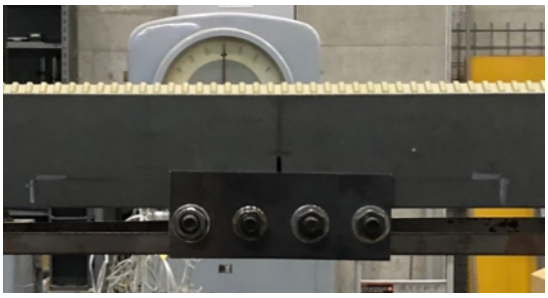

Fig. 3. Reinforcement for slit in the experiment.

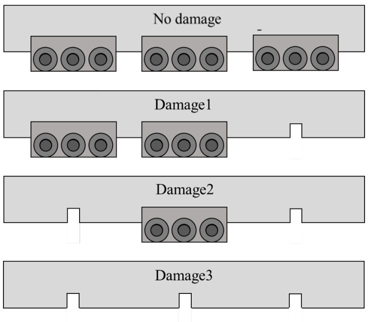

Fig. 4. Damage scenarios for the experiment.

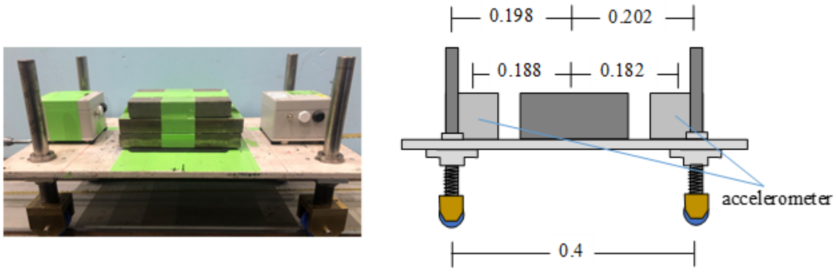

Fig. 5. Model vehicle used for the experiment. (unit: m)

Table 2 Vehicle properties in the experiment.

Property		Value
Body mass		22.9kg
Suspension stiffness	front	3480 N/m
	rear	3531 N/m
Suspension damping	front	3.51 N s/m
	rear	13.2 N s/m
Axle distance		0.4 m
First natural frequency		2.83 Hz

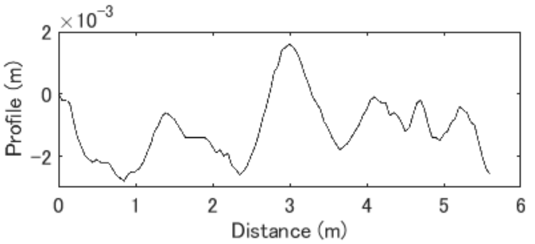

Fig. 6. Road surface roughness for the experiment.

The accelerometers are M-A550AC32x produced by Seiko Epson Corp., and the sampling frequency of the accelerometers was 200 Hz. Two steel rails are installed on the bridge as a runway track which is under the right and left wheels of the vehicle. The road surface roughness is carved on the rails, which is designed by decreasing the scale of the existing bridge's surface roughness of a 40.5 m long road shown in Fig. 6.

The vehicle speed is set considering the speed parameter which is a non-dimensional parameter defined in Eq. (1).

$$\alpha = \frac{v}{2f_{b,1}L} \tag{1}$$

where α stands for the speed parameter, v denotes the vehicle speed (m/s), $f_{b,1}$ expresses the natural frequency of the first bending mode of the bridge (Hz), and L signifies the bridge span length (m). In the experiment, vehicle speeds are changed as two patterns of 0.84 m/s and 1.26 m/s. Those correspond to 20 km/h and 30 km/h for a real bridge with a span length of 36 m.

3.2. *Result and Discussion*

For damage detection, the range of the BPF applied before estimating the difference is set between 2.3Hz and 3.3Hz, considering the first natural frequency of the bending mode of the bridge. The average of the measured accelerations for the body bounce motion and their PSDs in the reference step (No damage scenario) are shown in Fig. 7 and Fig. 8, respectively. Those are the results when the vehicle speed is 1.26m/s. In Fig. 8, there is a peak at 2.74Hz, which is considered to be caused by the natural frequency of both the vehicle and bridge (Chang et.al 2014).

The averages of the difference of the bounce accelerations between the reference and test steps are shown in Fig. 9, which are the results when the vehicle speed is 1.26m/s. Those results confirmed that greater damage severity is associated with greater amplitude of the difference of the bounce accelerations.

The RMS values of the difference of bounce accelerations at a vehicle speed of 1.26m/s in each run are plotted in Fig. 10. The RMS values are normalized so as that the average RMS values in No damage scenario in the reference step are equal to 1.0. Fig. 10 shows the higher correlation between the damage level and the RMS. The normalized RMS values of the difference of accelerations when the vehicle speed is 0.84m/s, is shown in Fig. 11. Result of one run is eliminated in Damage 2 because the calculated RMS is an abnormal outlier and there may be measurement error in Fig. 11. The RMS values of the difference of acceleration at the speed of 0.84m/s shows a clear correlation with damage level as well as when the vehicle speed is 1.26m/s, though the increase in the RMS value with respect to the damage level is smaller at the speed of 0.84 m/s than 1.26 m/s. The reason for the higher accuracy at higher speeds may be that the higher speed amplifies the bridge vibration and thus reduce the relative influence of noise and other undesirable factors in the measured accelerations.

To evaluate the existence and severity of bridge damage, the Mahalanobis Distance (MD) of the RMS values is used as a damage indicator. The MD is one of the distances which represents a statistical similarity among data groups, unlike the commonly used Euclidean distance. In anomaly detection, the MD between the reference data group and newly obtained data is calculated. If the MD is greater than a threshold, a possible anomaly is indicated. Such anomaly detection utilizing MD is called Mahalanobis-Taguchi System (MTS) (Taguchi & Jugulum 2000). In this study, the MD for i-th measured data in the test step is calculated as Eq. (2).

$$MD_i = \left|\frac{RMS_{test,i} - \mu_{ref}}{s_{ref}}\right| \tag{2}$$

where $RMS_{test,i}$ denotes the RMS of the i-th acceleration difference for the test step, μ_{ref} and s_{ref} represent the average and standard deviation of the RMS values of the acceleration difference in the reference step. The acceleration difference in the reference step is calculated by mutual subtraction among the reference accelerations as Eq. (3).

$$\mathbf{DIFACC}_{ref,i} = \mathbf{ACC}_{ref,i} - \frac{\sum_{j\neq i}\mathbf{ACC}_{ref,j}}{N-1} \tag{3}$$

where $\mathbf{DIFACC}_{ref,i}$ and $\mathbf{ACC}_{ref,i}$ indicate the vector of difference of acceleration and acceleration vector in the reference state respectively. Subscript i indicates i-th measured data in the reference measurement and N indicates the total number of measurements.

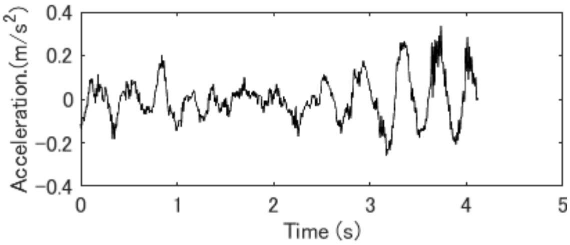

Fig. 7. Average acceleration of vehicle in the reference step.

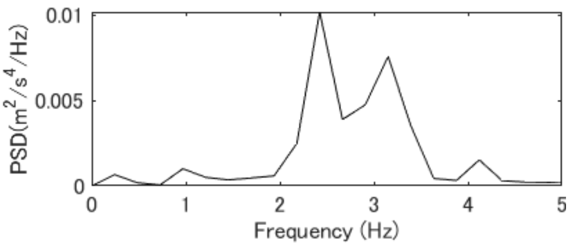

Fig. 8. Average PSD of vehicle acceleration in the reference step.

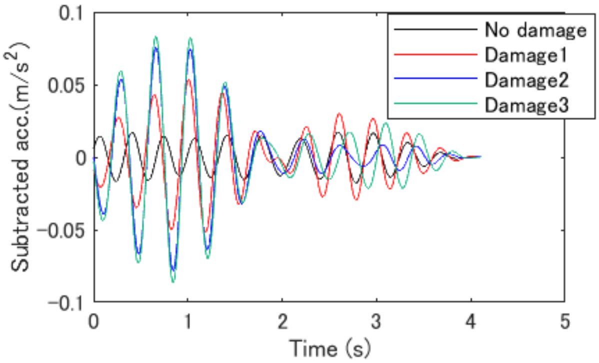

Fig. 9. Average of difference of accelerations in the reference step at vehicle speed of 1.26m/s.

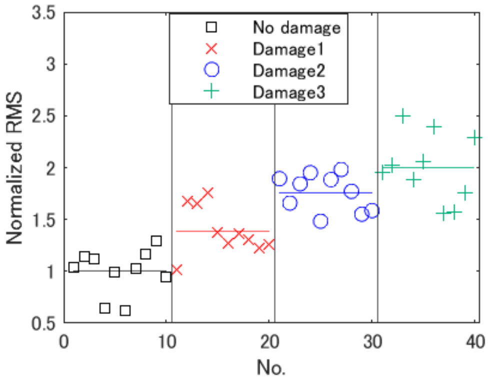

Fig. 10. Normalized RMS values of difference of accelerations at vehicle speed of 1.26m/s.

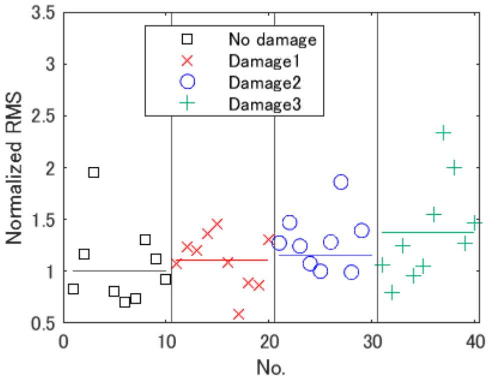

Fig. 11. Normalized RMS values of difference of accelerations at vehicle speed of 0.84m/s.

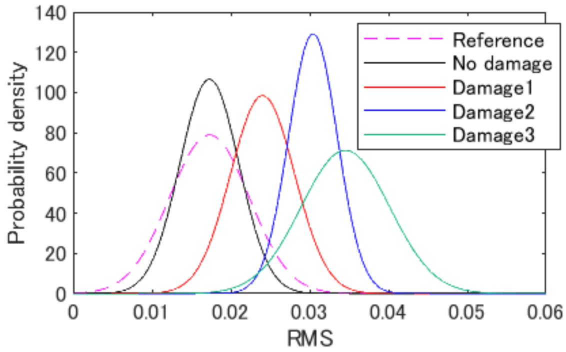

Fig. 12. Approximated normal distribution of RMS values for the acceleration differences at vehicle speed of 1.26m/s.

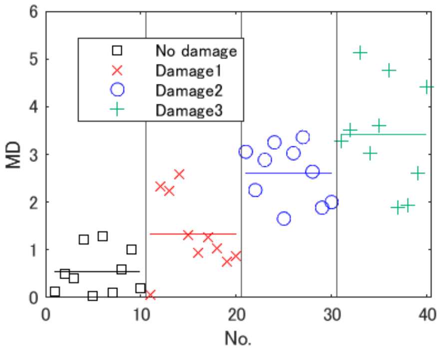

Fig. 13. Mahalanobis Distance (MD) of RMS values for the acceleration differences at vehicle speed of 1.26m/s.

Approximated normal distributions of the RMS values of difference of accelerations in the reference and all test states are summarized in Fig. 12. In Fig. 12, the normal distribution of the reference step and the No damage scenario in the test step has a similar mean value, while the mean values of the normal distributions for the damaged scenarios differ from the reference step as the damage severity increases.

The MD of the RMS value of the acceleration difference is shown in Fig. 13. The mean values of MD increase according to the increase in damage severity, which indicates the effectiveness of MD as a damage indicator.

4. CONCLUSIONS

The feasibility of drive-by bridge SHM using the difference of vehicle accelerations is investigated through the laboratory experiment, and following remarks are obtained. First, greater damage severity of a bridge is associated with a greater RMS value of the difference in vehicle accelerations. Second, it was observed that the MD also can be used to detect the damage level. It should be noted that the threshold of damage detection using MD for practical use should be determined by the field experiments in the future. There are also several limitations in the proposed method; a constant vehicle speed during measurements, the same vehicle speeds between the reference and test measurements, and no change in the road profile between the reference and test measurements. How to deal with or alleviate these difficult limitations remains as future work.

ACKNOWLEDGMENTS

A part of this work is supported by JSPS Bilateral joint research projects, Grant No. JPJSBP120217405, which is greatly appreciated.

REFERENCES

Chang, K.C., Kim, C.W. and Borjigin, S. 2014. Variability in bridge frequency induced by a parked vehicle, *Smart Structures and Systems*, 13(5): 755-773.

Gonzalez, A, O'Brien, E. J. and McGetrick, P. J. 2012. Identification of damping in a bridge using a moving instrumented vehicle, *Journal of Sound and Vibration*, 331:4115–4131.

Keenahan, J., O'Brien, E. J., Mcgetrick, P. J. and Gonzalez, A. 2014. The use of a dynamic truck–trailer drive-by system to monitor bridge damping, *Structural Health Monitoring*, 13(2):143–157.

Kim, C. W. and Kawatani, M. 2009. Challenge for a drive-by bridge inspection, Safety, Reliability and Risk of Structures, Infrastructures and Engineering Systems:758–765.

Kim, C. W., Isemoto, R., McGetrick, P. J., Kawatani, M. and O'Brien, E. J. 2014. Drive by bridge inspection from three different approaches, *Smart Structures and Systems*, 13(5): 775–796.

Lin, C.W. and Yang, Y.B. 2005. Use of passing vehicle to scan the fundamental bridge frequencies: An experimental verification, *Engineering Structures*, 27:1865–1878.

Malekjafarian, A. and O'Brien, E. J. 2014. Identification of bridge mode shapes using short time frequency domain decomposition of the responses measured in a passing vehicle, *Engineering Structures*, 81: 386–397.

Nagayama, T., Reksowardojo, A. P., Su, D. and Mizutani, T. 2017. Bridge natural frequency estimation by extracting the common vibration component from the responses of two vehicles, *Engineering Structures*, 150:821–829.

O'Brien, E. J., Mcgetrick, P. J. and Gonzalez, A. 2014. A drive-by inspection system via vehicle moving force identification, *Smart Structures and Systems*, 13(5):821–848.

Taguchi, G. and Jugulum, R. 2000. New trends in multivariate diagnosis, *Indian Journal of Statistics*, 62B: 233–248.

Tan, C., Elhattab, A. and Uddin, N. 2017. Drive-by bridge frequency-based monitoring utilizing wavelet transform, *Journal of Civil Structural Health Monitoring*, 7: 615–625.

Tan, C., Zhao, H., O'Brien, E. J., Uddin, N., Fitzgerald, P. C., McGetrick, P. J. and Kim, C. W. 2021. Extracting mode shapes from drive-by measurements to detect global and local damage in bridges, *Structure and Infrastructure Engineering*, 17:1582–1596.

Yang, Y.B, Lin, C.W. and Yau, J. D. 2004. Extracting bridge frequency from the dynamic response of a passing vehicle, *Journal of Sound and Vibration*, 272: 471–493.

Yang, Y. B., Li, Y. C. and Chang, K. C. 2014. Constructing the mode shapes of a bridge from a passing vehicle: A theoretical study, *Smart Structures and Systems*, 13(5):797–819.