EXPERIMENTAL INVESTIGATION OF DRIVE-BY BRIDGE INSPECTION

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This study presents ongoing research on a drive-by bridge inspection strategy, especially for short span bridges. Existing modal parameter-based bridge health monitoring approaches have difficulties in application to monitoring short span bridges. One of the underlying reasons is difficulty of actuating short span bridges effectively. Wind-induced ambient vibration is usually not expectable for these bridges. Applying actuators raises inspection costs. Using traffic-induced vibrations can provide a solution if the nonstationarity attributable to the moving vehicle is appropriately handled.

The inspection vehicle for the drive-by bridge inspection has three major functions; it acts as an actuator, a data acquisition system, and a message carrier. Three approaches to realize the drive-by inspection of short span bridges are the level 1 screening method which monitors bridge frequencies estimated from the vehicle's vibration data, the level 2 screening method based on the system parameter identification using vibration data of short span bridges under the moving inspection vehicle, and the level 3 screening method which uses vibration data from both the bridge and the inspection vehicle in order to identify damage. Feasibility of the approach is investigated through a laboratory moving vehicle experiment. Observations from the experiment demonstrate the feasibility of detecting changes in frequencies from vehicle vibrations, changes of dominant frequencies and damping constants from bridge vibrations and location and severity of damage.

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ABSTRACT: This study presents a vibration-based health monitoring strategy for short span bridges utilizing an inspection vehicle. How to screen health condition of short span bridges in terms of the drive-by bridge inspection is described. Feasibility of the drive-by bridge inspection is investigated through a scaled laboratory moving vehicle experiment. The feasibility of using an instrumented vehicle to detect the natural frequency and changes in structural damping of a model bridge is observed. Observations also demonstrate the possibility of diagnosis of bridges by comparing patterns of identified dynamic parameters of bridges through periodical monitoring. It is confirmed that the moving vehicle method identifies the damage location and severity well.

1 INTRODUCTION

Large portions of bridges located on municipalities are short span bridges, but have not been maintained properly because of budget restrictions of local governments. In Japan, for example, more than 85 per cent of bridges are classified as the short span bridge with span length between 15m and 50m. Developing a rapid and cost-effective tool for bridge health monitoring (BHM) focusing on short span bridges, therefore, is an important technical issue. How to excite short span bridges is another challenge for the vibration-based BHM because short span bridges are insensitive or sometimes impassive to external dynamic sources such as wind loads, ground vibrations, etc. Of course, the normal traffic excitations are important dynamic sources, but a cautious approach is required to use traffic-induced vibrations of short span bridges because the traffic-induced vibration is a kind of non-stationary process (Kim et al. (2005)).

Despite of the non-stationary property of traffic-induced vibrations of bridges, the traffic excitation is an attractive dynamic source for the vibration-based health monitoring of short span bridges. The idea to utilize traffic-induced vibrations for health monitoring of short span bridges is in the drive-by bridge inspection using an inspection vehicle. A strong point of the drive-by bridge inspection is the ready excitement by the inspection vehicle. Another advantage is its rapidity, since the inspection vehicle acquires and processes vibration data of bridges while traveling on bridges. The inspection vehicle also carries components of bridge vibrations. Therefore we can expect three major functions such as an actuator, data acquisition and message carrier from the inspection vehicle.

FHWA develops the HERMES as a drive-by inspection system just focusing on use of imaging radar for scanning bridge decks. Furukawa et al. (2007) employ vehicle's acceleration responses for pavement diagnostic. Interesting attempts to identify bridge frequencies using vehicle's vibration data are analytically examined by Yang et al. (2005) and McGetrick et al. (2009). However, those approaches are feasible for extracting the natural frequency of bridges within restricted conditions such as the bridge with very smooth roadway surface profiles.

Three levels of bridge condition screening based on the drive-by monitoring are proposed in this study, and feasibility of the proposed approaches is examined through a scaled laboratory experiment.

2 METHODOLOGY

Three major approaches for the drive-by bridge inspection are the level 1 screening method which monitors the bridge frequency estimated from the vehicle's vibration data, the level 2 screening method based on the modal parameter identification using vibration data transmitted from bridges to the inspection vehicle, and the level 3 screening method for the damage identification which uses data both from bridges and inspection vehicle.

It is noteworthy that the level 1 screening is adopted for a rapid health screening tool with sacrifice of the accuracy. The level 2 screening expecting to offer better information than the level 1 screening focuses on changes of identified frequencies, damping constants and mode shapes of bridges. The level 3 screening is adopted to identify damage location and severity when some diagnostic symptoms are detected through level 1 or level 2 screening. Theoretically feasibility of all methods is explainable using the dynamic equations of the bridge-vehicle interactive system shown in Figure 1.

To make the problem simple a 2DOF vehicle model is considered as shown in Figure 1, where $z_v(t)$ and $\theta_{vy}(t)$ respectively represent vehicle's bounce and pitching motions. In that figure, m_v denotes the vehicle mass. Additionally, k_{vs} and c_{vs} respectively denote the spring constant and damping coefficient at the s-th axle of the vehicle. The subscript s indicates the position of an axle: that is, s = 1 and s = 2 respectively signify the first (or front) and second (or rear) axles. Distances from the vehicle's center of gravity to respective axles are denoted by λ_{x1} and λ_{x2}. $z_0(x_s(t))$ indicates the roadway surface roughness at a position of $x_s(t)$ from the bridge entrance which is assumed as the reference position.

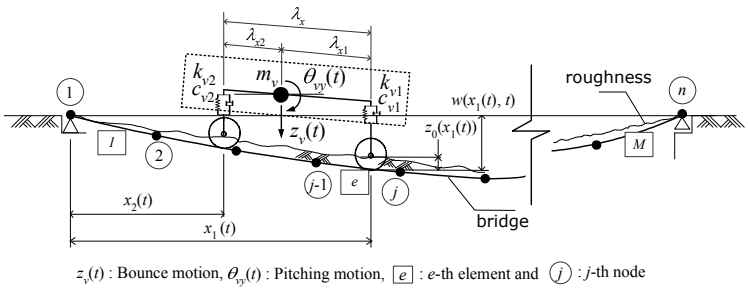


Figure 1. Scheme of a bridge-vehicle interactive system in moving vehicle laboratory experiment.

Equations of motion for the 2DOF vehicle can be formulated as shown in Eqs. (1) and (2). Therein $w(x_s(t), t)$ represents the time-variant displacement of the bridge at the contact point of the tire located $x_s(t)$ from the reference position.

$$m_v \ddot{z}_v(t) + \sum_{s=1}^{2} c_{vs}\left(\dot{z}_v(t) - (-1)^s \lambda_{xs}\dot{\theta}_{vy}(t) - \left(\dot{w}(x_s(t),t) - \dot{z}_0(x_s(t))\right)\right) + \sum_{s=1}^{2} k_{vs}\left(z_v(t) - (-1)^s \lambda_{xs}\theta_{vy}(t) - \left(w(x_s(t),t) - z_0(x_s(t))\right)\right) = 0 \quad (1)$$

$$m_v \lambda_{x1}\lambda_{x2}\ddot{\theta}_{vy}(t) - \sum_{s=1}^{2}(-1)^s \lambda_{xs} c_{vs}\left(\dot{z}_v(t) - (-1)^s \lambda_{xs}\dot{\theta}_{vy}(t) - \left(\dot{w}(x_s(t),t) - \dot{z}_0(x_s(t))\right)\right) - \sum_{s=1}^{2}(-1)^s \lambda_{xs} k_{vs}\left(z_v(t) - (-1)^s \lambda_{xs}\theta_{vy}(t) - \left(w(x_s(t),t) - z_0(x_s(t))\right)\right) = 0 \quad (2)$$

Combining the interaction force at the contact point of a vehicle wheel with the dynamic equation of motion of a bridge provides equations of motion for the bridge-vehicle interactive system. The dynamic equation of a bridge under a moving vehicle is definable as

$$\mathbf{M}_{br}\ddot{\mathbf{q}}_r(t) + \mathbf{C}_{br}\dot{\mathbf{q}}_r(t) + \mathbf{K}_{br}\mathbf{q}_r(t) = \sum_{s=1}^{2} \boldsymbol{\psi}_s(t) P(t) \quad (3)$$

where $\mathbf{M}_{br}$, $\mathbf{C}_{br}$ and $\mathbf{K}_{br}$ respectively represent the mass, damping, and stiffness matrices of the bridge. $\mathbf{q}_r(t)$ is the displacement vector; over dots denote derivatives with respect to time. $\boldsymbol{\psi}_s(t)$ is a load distribution vector to each node of the element on which a tire contacts. $P_s(t)$ in Eq. (3) denotes the wheel load at a tire and is definable as

$$P_s(t) = \left(1 - \frac{\lambda_{xs}}{\lambda_x}\right) m_v g + c_{vs}\dot{\delta}_s(t) + k_{vs}\delta_s(t) \quad (4)$$

where, $\delta_s(t)$ denotes the relative vertical displacement at the s-th axle of the vehicle and is definable as

$$\delta_s(t) = z_v(t) - (-1)^s \lambda_{xs}\theta_{vy}(t) - \left\{w(x_s(t),t) - z_0(x_s(t))\right\} \quad (5)$$

A goal for the level 1 screening is extracting changes of bridge's dynamic features from the vehicle vibrations since dynamic equations of motion of the vehicle traveling on a bridge clearly contain bridge's responses $w(x_s(t), t)$ as shown in Eqs. (1) and (2). It means that if dynamic properties between the vehicle and bridge are clearly different and moreover the amplitude of the bridge response is big enough then detecting bridge's frequencies becomes feasible theoretically.

Both level 2 and level 3 screenings basically rely on bridges' vibration data actuated by the inspection vehicle travelling on the bridge. The discrepancy between two methods is in the use of external forces generated by the moving vehicle. In other words, the level 2 screening is an output only method. On the other hand, the level 3 screening needs both bridge's vibration data and vehicle's dynamic wheel loads.

The eigensystem realization algorithm (ERA) (Pappa and Ibrahim (1981)) based on the state space equation of the dynamic system is adopted for the level 2 screening. Details of the process are obtainable from the reference (e.g. Gersch et al. (1973)). From Eq. (3) the state vector $\mathbf{x}(t)$ for the equation of motion of a bridge under a moving vehicle is definable as

$$\mathbf{x}(t) = \begin{bmatrix} \mathbf{q}_r(t) \\ \dot{\mathbf{q}}_r(t) \end{bmatrix} \tag{6}$$

If $\mathbf{y}(t) \in \mathbf{R}^m$ denotes output of the bridge taken from m observation points, then the corresponding state equation of a continuous-time system is described as

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{w}(t) \tag{7}$$

$$\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) \tag{8}$$

where, **A**, **B** and **C** respectively denote system, input influence and output influence matrices. Especially, **C** is a transformation matrix mapping the position of system degrees of freedom with measured outputs which consists of zero or one. **w**(t) denotes external effects (or noise term) for the system.

The AR model (e.g. Kim et al. (2010)) is adopted to identify the system **A** of Eq. (7) by assuming white noise excitations. Traffic-induced vibrations observed in operation are not due to a white noise excitation actually, but nevertheless the idea of the level 2 screening even using traffic-induced vibrations of short span bridges for system identification is that repeatedly identified system parameters under a given moving vehicle can provide a pattern or even a statistical one which may give useful information to make a decision for the bridge's health condition.

The concept of the level 3 screening is based on the fact that the stiffness distribution in the structure changes as a result of damage. This change is detectable by measuring dynamic responses in the inspection vehicle whose dynamic wheel loads or dynamic properties are known. The linear equation for the bridge's structural stiffness can also be derived from Eq. (3) as shown in Eq. (9) which is a pseudo-static formulation showing change of structural stiffness (Kim and Kawatani (2008)).

$$\mathbf{K}_{br}\mathbf{q}_r(t) = \mathbf{f}(t);\ \mathbf{f}(t) = \sum_{s=1}^{2} \boldsymbol{\psi}_s(t) P_s(t) + \mathbf{M}_{br}\ddot{\mathbf{q}}_r(t) + \mathbf{C}_{br}\dot{\mathbf{q}}_r(t) \tag{9}$$

The change of stiffness $\mathbf{K}_{br}$ in Eq. (9) indicates a change in the bridge's stiffness due to damage. Detecting the change in $\mathbf{K}_{br}$ is the basic concept of the damage identification proposed for the level 3 screening. The change of the element stiffness is also obtainable using the element stiffness index (ESI) as

$$\mu_e = \mathbf{K}_d / \mathbf{K}_i \tag{10}$$

where μ_e is the element stiffness index, and $\mathbf{K}_i$ and $\mathbf{K}_d$ signify the stiffness of the e-th element of an intact and damage states, respectively.

Estimating the ESI is the final goal for the level 3 screening. A noteworthy point is that the ESI value is unity for intact state, meaning that the value is less than unity for damaged members. Kim and Kawatani (2008) show details of the methodology.

3 EXPERIMENT

A scaled moving vehicle laboratory experiment is performed to investigate feasibility of the drive-by health monitoring. The experiment setup is summarized in Figure 2. Roadway profiles are also considered in the experiment.

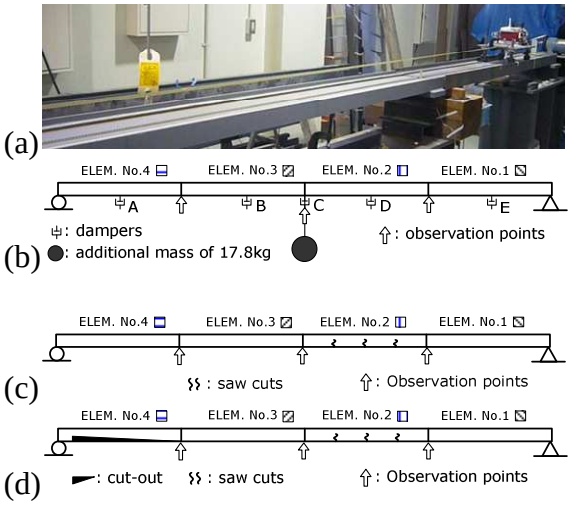


Figure 2. Experiment setup, observation points and damage scenarios: (a) model bridge under moving vehicle; (b) experimental setup for level 1 screening; (c) for level 2 and 3 screenings with damage scenario of D1; and (d) for level 2 and 3 screenings with damage scenario of D2.

As for the experiment to examine the feasibility of the level 1 screening, the damping of the bridge is varied in this experiment by applying old displacement transducers at particular points on the bridge in addition to a mass of 17.8kg added at midspan. The layout of these transducers is illustrated in Figure 2 (b), in which the dampers are denoted by the letters, A to E. The old transducers are used as they provide frictional resistance to bridge displacements at the chosen locations. The damping constant changes from 1.4% for the initial case to 2.1% and 4.3% due to an additional damper at the span center and five additional dampers respectively. The additional mass is used to adjust the frequency of the bridge as frequently damage which causes changes in damping may cause some change in frequency. The additional mass causes change of the natural frequency for the first bending mode from 2.7Hz to 2.5Hz.

Two damage scenarios are considered in the experiment to investigate feasibility of the level 2 and level 3 screenings: as for the first damage scenario (hereafter D1), three saw cuts are applied to both sides of web plates at ELEM No.2 of the bridge; the second damage scenario (hereafter D2) considers both saw cuts at ELEM No.2 and cut-out at ELEM. No.4. For damage scenario D1, the bending rigidity of the member decreases to around 89 % of the intact state. About 23 % loss of bending rigidity of the damaged member is observed due to damage scenario D2. Damage changes the natural frequencies of the bridge: 2.6Hz under damage scenario D1; and 2.5Hz under damage scenario under damage scenario D2. Apparently the damage causes decrease in natural frequencies.

During the experiment, three different vehicle models of which the natural frequency of the bounce motion is changeable using a different set of mass and spring, are considered in the experiment. Three vehicles, called as VT-A, VT-B and VT-C, are used in the experiment. Natural frequencies for the bounce motion of those vehicle models are respectively 2.93 Hz, 3.76 Hz and 3.03 Hz. Two different speeds of S1=0.93 m/s and S2=1.63 m/s are considered in order to investigate the effect of the vehicle speed on the screening results. Therefore six traffic scenarios are considered: SCN1 of VT-A vehicle traveling with speed of S1; SCN2 of VT-A vehicle traveling with speed of S2; SCN3 of VT-B vehicle traveling with speed of S1; SCN4 of VT-B vehicle traveling with speed of

S2; SCN5 of VT-C vehicle traveling with speed of S1; and SCN6 of VT-C vehicle traveling with speed of S2.

4 CONDITION SCREENING

4.1 Level 1 screening

Figure 3 compares the mean acceleration spectra of the model bridge and vehicle obtained in all scenarios for 5 crossings of vehicle VT-A at speed S1. The bridge frequency peak at 2.44 Hz occurs in both Figures 3(a) and (b). It can be seen that as the damping increases, i.e., from 'Intact' to 'C' to 'ABCDE', the peak magnitude at the bridge frequency in the vehicle spectra decreases. This trend also occurs at the peak in vehicle spectra at 3.91 Hz. This suggests the feasibility of detecting changes in bridge damping from vehicle vibrations. It is noteworthy that the dominant frequency of bridge in Figure 3(a) is biased from the natural frequencies of the bridge and vehicle, which shows difficulty in distinguishing the bridge's natural frequency from traffic-induced vibrations.

For all scenarios investigated but omitted in this paper, the bridge frequency was identified in the vehicle spectra. It is clear that selection of vehicle speed is an important factor in the detection of the bridge frequency. The higher speed, S2 = 1.63m/s, provides larger magnitude peaks in the spectra but the spectral resolution is not as high as for speed S1. For VT-A vehicle and speed of S1, changes in damping are detected in the vehicle spectra. These results indicate that to confirm the feasibility of the system, further investigation of vehicle configuration, speed and girder damping scenarios is necessary.

4.2 Level 2 screening

System parameters of the intact and damaged model bridges are identified by the AR model. The change of identified system parameters such as dominant frequencies and corresponding damping constants is investigated. The reason to take notice of dominant dynamic parameters is that traffic-induced bridge vibrations are usually affected by vehicle's dynamic properties and the identified system parameters are not bridge's but those of bridge-vehicle interactive system. Therefore this study focuses on the dominant dynamic parameters instead of natural modal parameters.

Dominant system frequencies and damping constants are indentified using the data taken from six traffic scenarios. A part of the results is shown in Figure 4, in which the solid circles are identified results of the intact bridge under vehicle speed S2=1.63m/s, and solid triangles and solid squares respectively denote the those identified parameters from the damaged bridges D1 and D2 under vehicle speed of S2. Those of empty are the identified results under vehicle speed S1=0.93m/s. It demonstrates increasing influence of the vehicle system to bridge vibrations with increasing speed. In other words the identified results under higher vehicle speeds yield to more biased results than those of lower speeds. However those frequencies and damping constants of lower mode such as around 2.7Hz, which are omitted in this paper, were more greatly scattered comparing with higher modes.

A clear change of identified dominant frequencies can be read from Figure 4 despite of their variations. Even for damping constants which usually show larger variances than

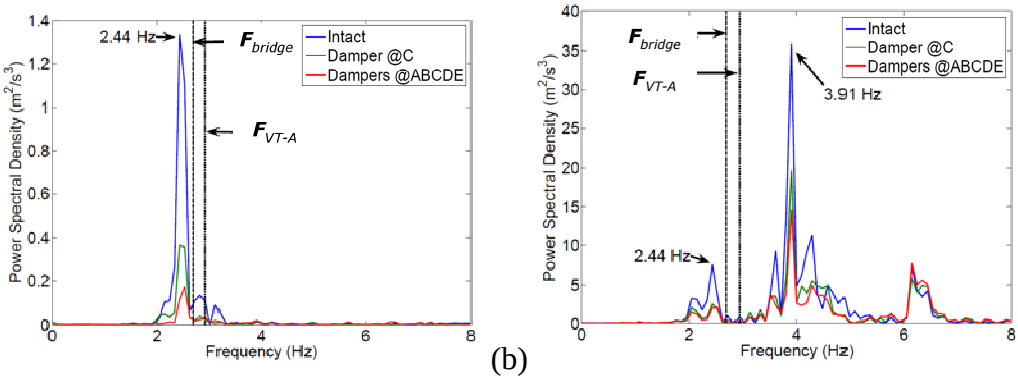
that of the identified frequency, the change of identified damping constants due to the damage is apparent.

4.3 Level 3 screening

This section discusses the feasibility of the level 3 screening which aims to identify damages. Identified ESI values for D1 and D2 are summarized in Figure 5. For D1, the damage on the element No.2 is well identified by the proposed method except SCN3 (see Figure 5(a)), the loading scenario 3, which identifies ELEM. No.1 as the most suspected damage member rather than ELEM. No.2. Unfortunately the reason for the unsuccessful identification is not clear yet.

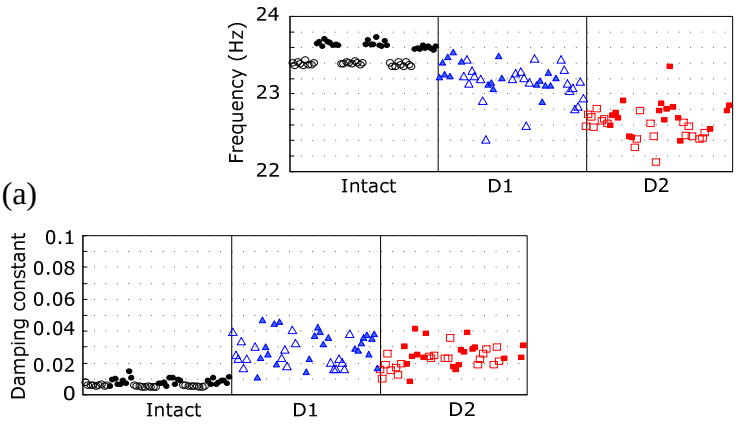
The error relating to identifying severity of damages is also appeared in Figure 5. The error varies up to 4.5 %, and it demonstrates the proposed method can also presume the damage severity. Suspected damage locations and severity of the damage scenario D2 are also well identified as shown in Figure 5(b).

Observations from the experimental investigation demonstrate that the location and severity of damages are constantly identified without great variation according to vehicle type and speed, even though the vehicle with similar frequency characteristics with bridge's fundamental frequency and higher speed may give better chance to identify both severity and location.



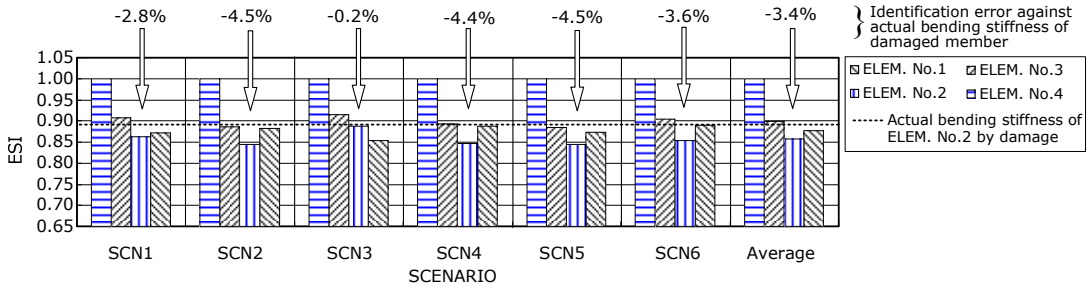
(a) (b)

Figure 3. Spectra of mean acceleration responses: VT-A for speed S1 of 0.93m/s: (a) bridge midspan; and (b) front axle of vehicle.

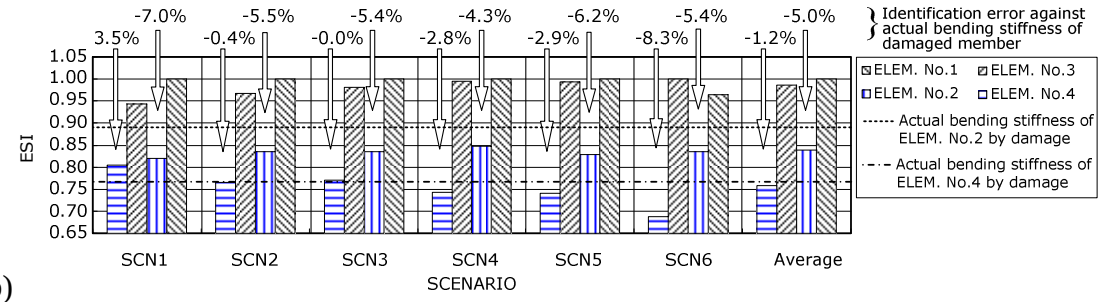


(a) (b)

Figure 4. Variation of identified frequencies and ddamping constants for level 2 screening: (a) observed freqeucny near 23Hz; and (b) observed damping constant corresponding to the frequency near 23Hz.



(a)



(b)

Figure 5. Identified damage location and severity by level 3 screening: (a) D1; and (b) D2.

5 CONCLUSIONS

This study investigates feasibility of the drive-by bridge health monitoring through a scaled laboratory moving vehicle experiment. The summarized results are as follows.

The bridge frequency was identified in the vehicle spectra. It is clear that selection of vehicle speed is an important factor in the detection of the bridge frequency. The higher speed provides larger magnitude peaks in the spectra but the spectral resolution is not as high as for lower speed. Changes in damping are detected in the vehicle spectra. Observations indicate possibility to detect the bridge frequency and changes in damping from the acceleration measurements of a moving vehicle.

A clear change of identified dominant frequencies and damping constants is observed despite of their variations, which demonstrates feasibility of making decision for the health condition of short span bridges from change of identified system parameters using the traffic-induced vibration data.

Location and severity of damages are constantly identified without great variation according to vehicle type and speed, even though the vehicle with similar frequency characteristics with bridge's fundamental frequency and higher speed may give better chance to identify both severity and location.

Many further investigations are necessary to make the method practically applicable, such as how sensitive the method is under various kinds of damages, even though feasibility of the drive-by bridge inspection was observed through the laboratory experiment. Another great challenge is realizing data acquisition both from moving vehicle and bridge simultaneously.

6 ACKNOWLEDGMENT

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