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Effect of road surface roughness on indirect approach for measuring bridge frequencies from a passing vehicle

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Abstract. The indirect approach for measuring the bridge frequencies from the dynamic responses of a passing vehicle is a highly potential method. In this study, the effect of road surface roughness on such an approach is studied through finite element simulations. A two-dimensional mathematical model with the vehicle simulated as a moving sprung mass and the bridge as a simply-supported beam is adopted. The dynamic responses of the passing vehicle are solved by the finite element method along with the Newmark β method. Through the numerical examples studied, it is shown that the presence of surface roughness may have negative consequence on the extraction of bridge frequencies from the test vehicle. However, such a shortcoming can be overcome either by introducing multiple moving vehicles on the bridge, besides the test vehicle, or by raising the moving speed of the accompanying vehicles.

Keywords: road surface; roughness; bridge; frequencies; passing vehicle.

1. Introduction

Conventionally, to measure the vibration frequencies of a bridge requires that the sensors be mounted on the bridge. Such an approach has been popularly used and is called the *direct approach*. In contrast, the bridge frequencies can also be measured in an indirect way from the dynamic response of a test vehicle traveling over the bridge. Such an approach is called the *indirect approach*.

The key idea of the indirect approach is that the passing vehicle plays the dual role of a vibration exciter to the bridge and a message receiver of the bridge responses. By performing spectral analysis to the dynamic responses recorded for the vehicle during its passage over the bridge, it is verified, theoretically and experimentally, that the bridge frequencies dominate the vehicle responses and therefore can be extracted from the latter (Yang *et al*. 2004a, Yang and Lin 2005, Lin and Yang 2005, Chang and Yang 2007). With the vibration sensors installed on the moving test vehicle, rather than on the bridge deck as was conventionally done by the direct approach, the indirect approach for measuring the bridge frequencies from the moving test vehicle reveals the advantage of being fast, convenient, and portable.

In the pioneering studies for the indirect approach, road surface roughness was neglected (or not

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discussed thoroughly) in the mathematical modeling for simplification, but still kept within the scope of feasibility study, i.e., to explore the feasibility of measuring bridge frequencies from a passing vehicle, through either analytical derivation or numerical simulation. Since road surface roughness is also an important factor in the vehicle-bridge interaction problem, its effect on the indirect approach, especially on the feasibility of measuring bridge frequencies from a passing vehicle, is of great interest to engineers.

The main objective of this study is to explore the effect of road surface roughness on the indirect approach for measuring bridge frequencies from a passing vehicle through the finite element simulations. To this end, the governing equations of vehicle-bridge interaction (VBI) element in consideration of road surface roughness will be derived first, which is an extension of the previous works on vehicle-bridge interaction (Yang and Yau 1997, Yang *et al*. 2004b, Yau 2009). Then the procedure and parametric settings for numerical simulations will be introduced to generate the dynamic response data of the passing vehicle under the conditions specified. To evaluate the individual effect of surface roughness, the results obtained from the case with vehicle moving over a rigid surface with roughness will be compared to those over a bridge with no surface roughness. Also, the effect of different levels of surface roughness on the dynamic responses of the passing vehicle will be studied. To extend the applicability of the indirect approach, two situations will be considered herein: one is to introduce multiple passing vehicles, in addition to the test vehicle, and the other is to change the speed of the accompanying vehicles. Based on these studies, concluding remarks will be drawn at the end of the paper regarding the feasibility of the indirect approach for extracting the bridge frequencies from a test vehicle passing over the bridge with road surface roughness.

2. Derivation of Vehicle-Bridge interaction element

Fig. 1 shows the mathematical model for the vehicle-bridge interaction system considered in this study, in which the vehicle is modeled as a moving sprung mass m_v, supported by a spring of stiffness coefficient k_v and by a dashpot of damping coefficient c_v, and the bridge as a simply-supported beam of length L. The dynamic responses of both the moving vehicle and bridge are calculated by the finite element method. To account for the interactive behavior between the sprung mass and beam, the vehicle-bridge interaction (VBI) element is adopted in this study, as introduced below.

A typical VBI element with surface roughness is shown in Fig. 2, in which the vehicle is modeled

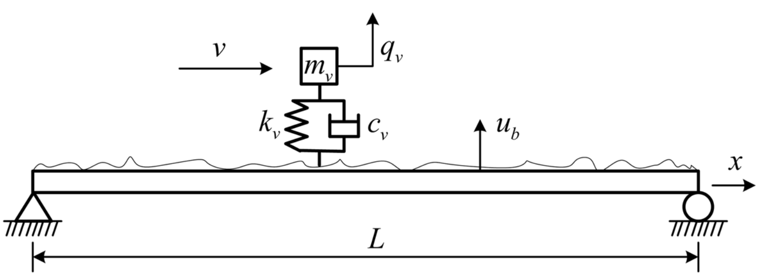


Fig. 1 Mathematical model for vehicle-bridge interaction system

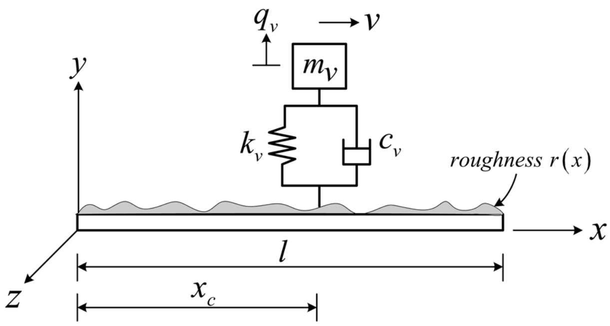


Fig. 2 Vehicle-bridge interaction element

as a sprung mass with single degree of freedom (DOF) and the beam element as a 12-DOF system. The equations of motion for the sprung mass and the beam element directly in contact can be written as

$$m_v\ddot{q}_v + c_v\frac{d}{dt}(q_v - \langle N\rangle_c\{q_b\} - r_c) + k_v(q_v - \langle N\rangle_c\{q_b\} - r_c) = 0 \tag{1}$$

and

$$[m_b]\{\ddot{q}_b\} + [c_b]\{\dot{q}_b\} + [k_b]\{q_b\} = f_c\{N\}_c \tag{2}$$

respectively, where q_v denotes the vehicle displacement, r_c the road surface roughness evaluated at the position x_c of the contact point, $\{u_b\}$ the displacement vector, $[m_b]$, $[c_b]$, $[k_b]$ the mass, damping, stiffness matrices of the bridge element, $\{N\}$ a vector containing the cubic Hermitian interpolation functions, and $\{N\}_c$ represents the vector $\{N\}$ calculated at x_c. The contact force f_c between the vehicle and bridge can be expressed as

$$f_c = -m_v g + c_v\frac{d}{dt}(q_v - \langle N\rangle_c\{q_b\} - r_c) + k_v(q_v - \langle N\rangle_c\{q_b\} - r_c) \tag{3}$$

Eqs. (1) and (2) can be derived and combined as a set of equations of motion for the VBI element as follows

$$\begin{bmatrix} m_v & 0 \\ 0 & [m_b] \end{bmatrix}\begin{Bmatrix} \ddot{q}_v \\ \{\ddot{q}_b\} \end{Bmatrix} + \begin{bmatrix} c_v & -c_v\{N\}_c^T \\ -c_v\{N\}_c & [c_b] + c_v\{N\}_c\{N\}_c^T \end{bmatrix}\begin{Bmatrix} \dot{q}_v \\ \{\dot{q}_b\} \end{Bmatrix}$$

$$+ \begin{bmatrix} k_v & -c_v v\{N'\}_c^T - k_v\{N\}_c^T \\ -k_v\{N\}_c & [k_b] + c_v v\{N\}_c\{N'\}_c^T + k_v\{N\}_c\{N\}_c^T \end{bmatrix}\begin{Bmatrix} q_v \\ \{q_b\} \end{Bmatrix}$$

$$= \begin{Bmatrix} c_v v r_c' + k_v r_c \\ -c_v v r_c'\{N\}_c - k_v r_c\{N\}_c - m_v g\{N\}_c \end{Bmatrix} \tag{4}$$

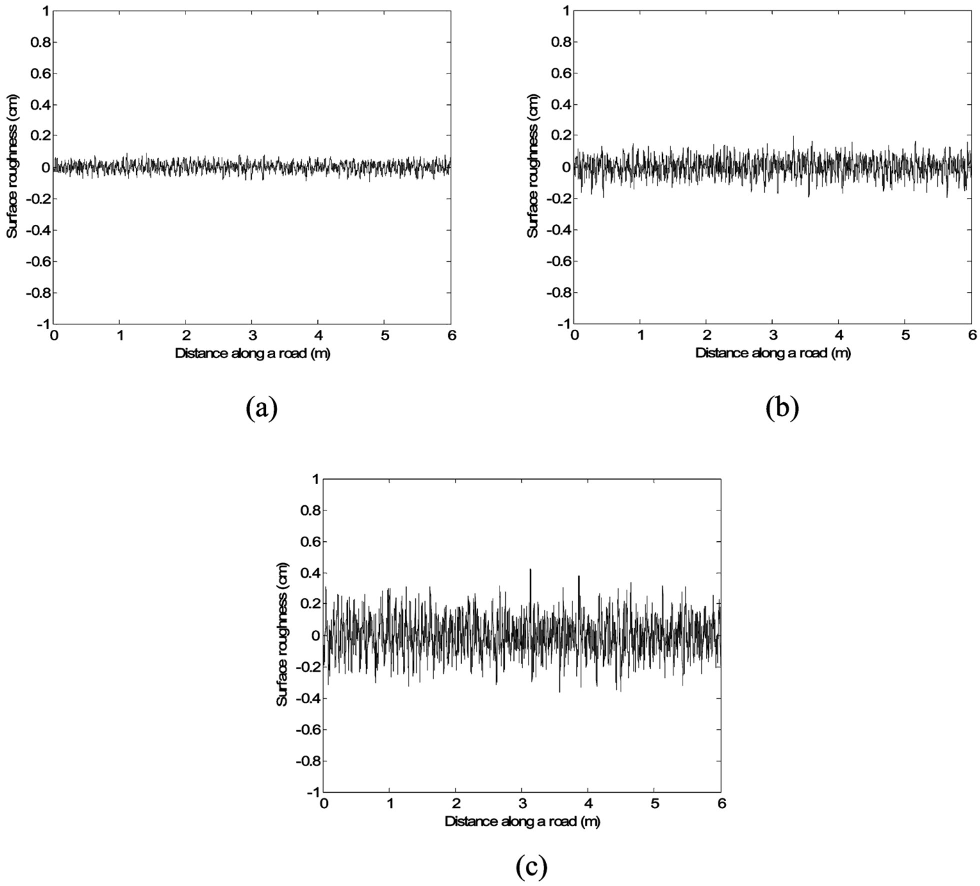


Fig. 3 Profiles of road surface roughness: (a) good, (b) average, (c) poor

3. Numerical simulation

For beam elements that are not acted upon by the sprung mass, they are modeled as conventional 12-DOF beam elements. Assembling the VBI element with the other conventional bridge elements to yield the equations of motion for the whole system, and then applying the Newmark β method to solve the motion equations, one can solve the dynamic responses of both the sprung mass and bridge for the time step considered.

In order to make the simulation results reflect more realistic cases, the data of the simple beam are selected based on those used for a real bridge (Lin and Yang 2005) as follows: length $L = 30$ m, elastic modulus $E = 27.5$ GPa, mass per unit length $\overline{m} = 1000$ kg/m, and moment of inertia $I = 0.175$ m^4. The properties selected for the vehicle are $m_v = 120$ kg, $k_v = 170$ kN/m, and $c_v = 0$. As for road surface roughness, it is generated according to the PSD curve presented in ISO8608 (1995), with the spacial frequency of interest ranging from 1 to 100 m^{-1}. The simulated profiles of road surface roughness classified as good (class A in ISO8608), average (class C), and poor condition (class E) are shown as Figs. 3(a), (b), and (c), respectively.

Among the various responses of a passing vehicle, only the acceleration responses are calculated

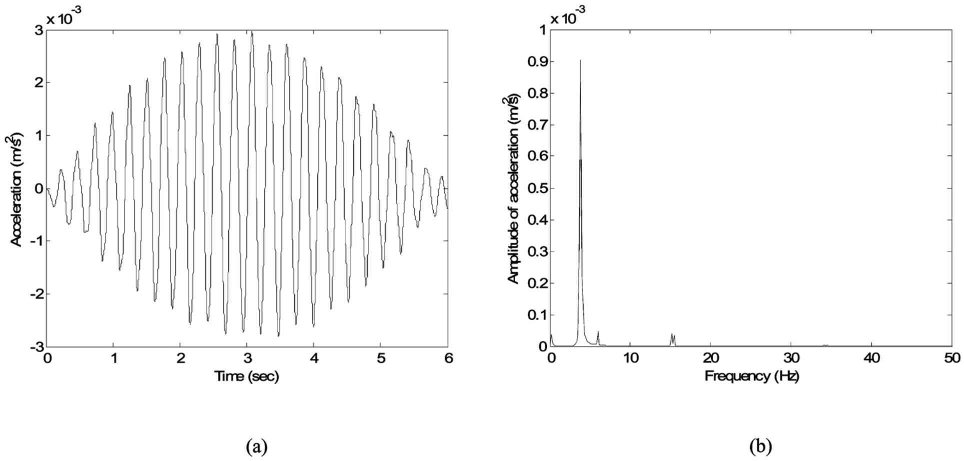


Fig. 4 Responses of vehicle passing through the bridge with smooth surface: (a) acceleration response, (b) spectrum

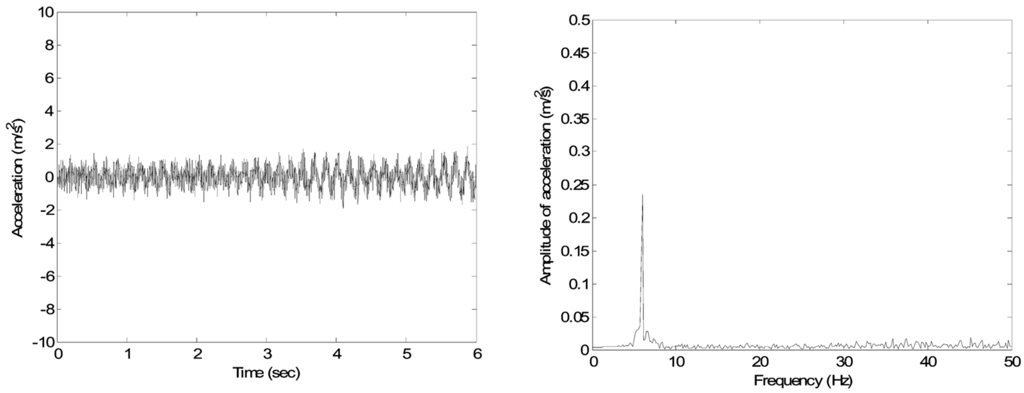
and analyzed herein since they are exactly the dynamic responses of the passing vehicle that are recorded for extraction of the bridge frequencies (Yang and Lin 2005). To be brief, the term "acceleration response" will be referred to merely as "response" from here on.

4. Effect of road surface roughness

To evaluate the effect of road surface roughness on the dynamic response of the test vehicle, two cases are considered herein: one with vehicle moving on a bridge with smooth surface and the other with vehicle moving over a rigid ground with roughness. For the former case, in the absence of surface roughness, the responses of the passing vehicle are induced by the interaction between the bridge and vehicle. For the later case, the rigid ground will not vibrate as the vehicle moves over it, implying no interaction between the ground and the vehicle, so the responses of the passing vehicle are purely those induced by the surface roughness. The vehicle has a constant speed of 5 m/s for both cases and the roughness of good condition are adopted for the later case. The responses of the passing vehicle for the two cases, along with their corresponding Fourier spectra, are plotted in Figs. 4 and 5, respectively.

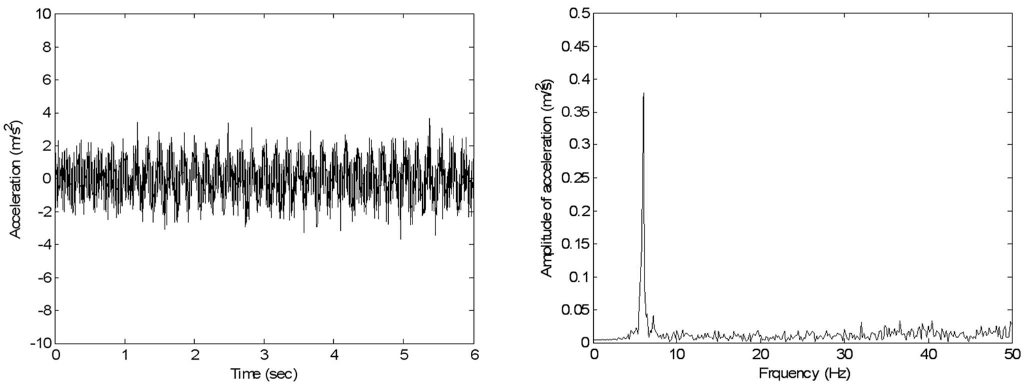
In Fig. 4(a), the maximum response of the vehicle passing through the bridge with smooth surface is about 0.003 m/s^2, while, in Fig. 5(a), that of the vehicle moving on the rigid ground with roughness reaches about 2 m/s^2. The implication herein is that the responses of the vehicle induced by the vehicle-bridge interaction are much less than those induced by the surface roughness. A similar observation can also be made from the related acceleration spectra: the amplitude of acceleration corresponding to the bridge's natural frequency of the first mode (about 3.83 Hz in Fig. 4(b)) is about 0.0009 m/s^2, while that corresponding to the vehicle's frequency (about 5.99 Hz in Fig. 5(b)) reaches about 0.25 m/s^2.

As for the effect of surface roughness of different levels on the responses of the passing vehicle, three different cases are considered: each with the vehicle moving over the rigid ground with roughness of good, average, and poor condition. The responses of the vehicle, along with their



(a) (b)

Fig. 5 Responses of vehicle moving on rigid surface with roughness (good condition): (a) acceleration response, (b) spectrum



(a) (b)

Fig. 6 Responses of vehicle moving on rigid surface with roughness (average condition): (a) acceleration response, (b) spectrum

corresponding spectra, for those three cases are sequentially shown in Figs. 5-7.

As was mentioned above, the maximum response of the vehicle moving over the rigid ground of good condition is about 2 m/s^2, and the amplitude of the vehicle's frequency component is about 0.25 m/s^2. As the roughness condition goes poorer (from good, average, to poor condition), the maximum response of the moving vehicle becomes larger (approximately from 2, 4, to 7 m/s^2), and the amplitude of the vehicle's frequency component becomes larger as well (approximately from 0.25, 0.37, to 0.43 m/s^2). Needless to say, the responses induced by the surface roughness of poorer conditions are much greater than those induced by the vehicle-bridge interaction. The above observation matches well with intuitive consciousness.

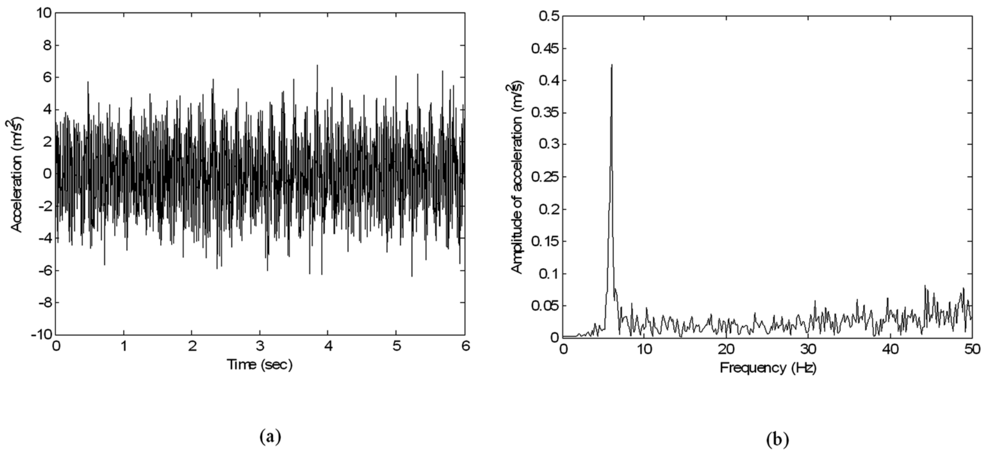


Fig. 7 Responses of vehicle moving on rigid surface with roughness (poor condition): (a) acceleration response, (b) spectrum

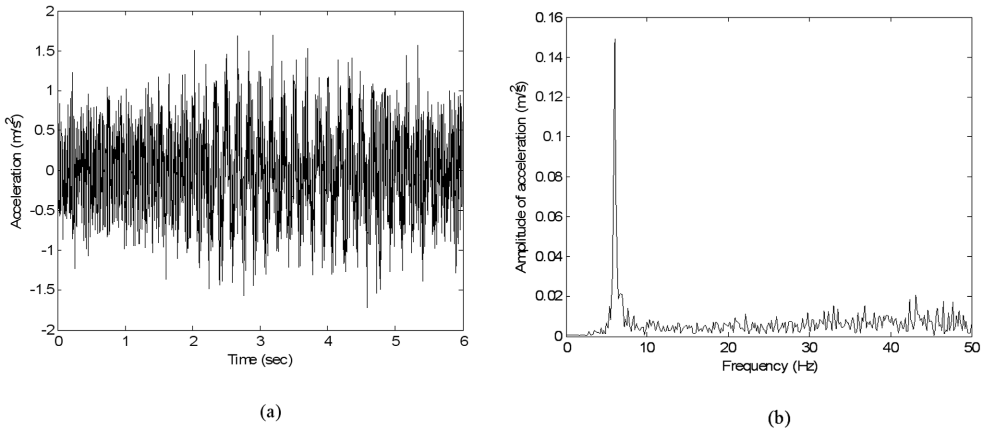


Fig. 8 Responses of single vehicle passing though the bridge with surface roughness: (a) acceleration response, (b) spectrum

5. Indirect approach in consideration of road surface roughness

To clarify the effect of road surface roughness on the measurement of bridge frequencies from a passing vehicle, a typical case with the single vehicle passing through the bridge with surface roughness (of good condition) is first studied. Fig. 8 shows the response of the vehicle and its corresponding spectrum for this case. It is observed from Fig. 8(b) that only the peak corresponding to the vehicle frequency ($\omega_v = 5.99$ Hz) can be identified, but the same is not true with the bridge frequency. The reason is that during its passage over the bridge, the vehicle's responses are excited by two major sources: one is the bridge vibration induced by vehicle-bridge interaction and the other the random oscillation caused by road surface roughness. From the results obtained in Section 4, it is inferred that the amplitude of the bridge-related frequency component induced by vehicle-

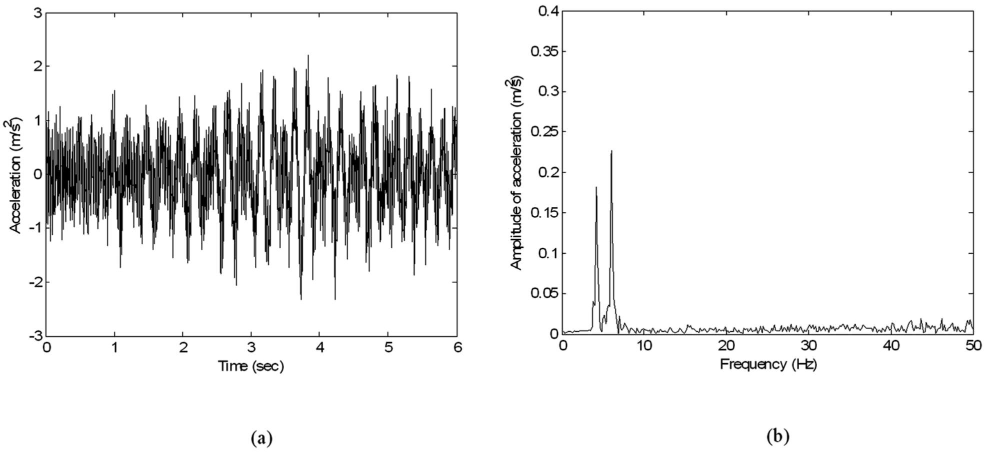


Fig. 9 Responses of test vehicle passing though the bridge with surface roughness ($v = 5$ m/s): (a) acceleration response, (b) spectrum

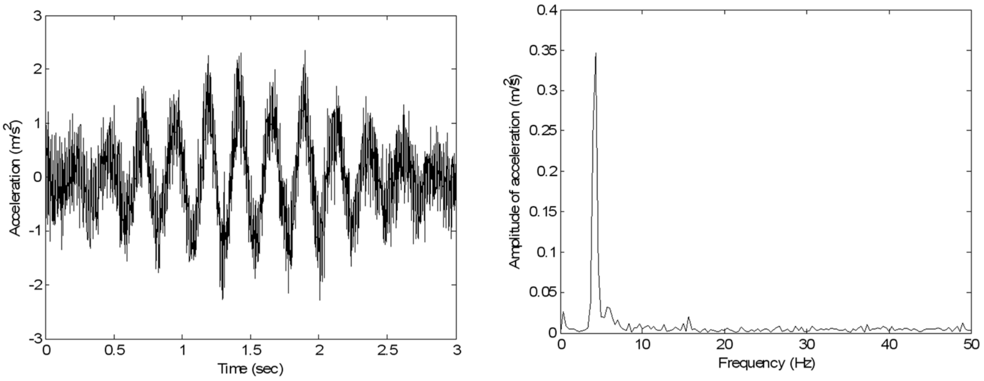
bridge interaction is much less than that of the vehicle frequency component induced by road surface roughness. The comparatively small amplitude of the bridge-related frequency component may have negative consequence for extraction of the bridge frequency, making it difficult to identify the bridge frequencies.

To overcome the difficulty caused by the presence of surface roughness, two ways are considered herein: one is to introduce multiple moving vehicles, in addition to the test vehicle, and the other is to elevate the moving speed of the accompanying vehicles.

For the first case, five sequential vehicles are allowed to move over the bridge, including the middle one as the test vehicle, whose responses are calculated and compared with those of the single vehicle previously considered. The properties of the test vehicle remain the same as those of the single vehicle previously considered, i.e. $m_v = 120$ kg, $k_v = 170$ kN/m, and $c_v = 0$. The properties of the other four accompanying vehicles are set as follows: mass = 5000 kg, stiffness coefficient = 500 kN/m, and damping coefficient = 0. The five sequential vehicles are assumed to move at the speed of 5 m/s and with an equal spacing of 1 m. The response of the test vehicle and its corresponding spectrum are shown in Fig. 9.

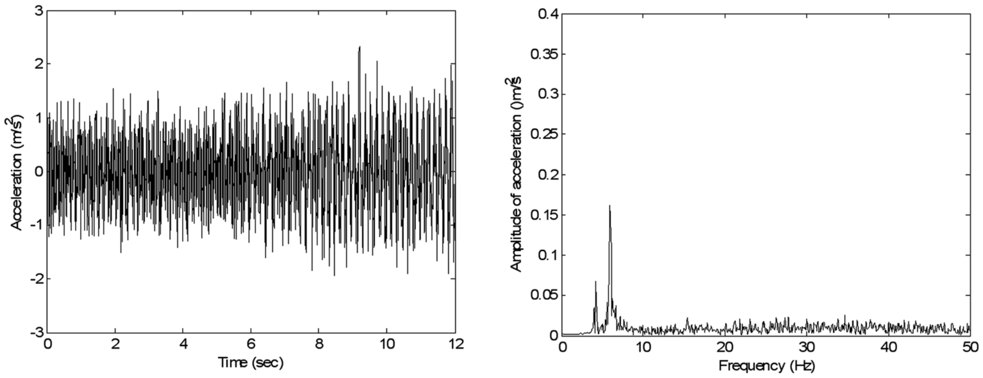
Comparing the acceleration spectrum of the test vehicle traveling along with sequential vehicles (Fig. 9(b)) to that of the single vehicle case (Fig. 8(b)), it is observed that, besides the vehicle frequency, the bridge frequency (about 3.83Hz) can be clearly identified in the acceleration spectrum (Fig. 9(b)). The bridge frequency becomes identifiable simply because the bridge vibration response has been amplified by the passage of additional accompanying vehicles. Then, in the test vehicle response, the response component related to the bridge vibration is simultaneously amplified by the larger bridge response, to a level that approaches or even exceeds the response component purely induced by the surface roughness. Such an observation agrees well with one of the results presented by Yang and Chang (2009): the smaller the initial vehicle/bridge acceleration amplitude ratio, the greater the probability of successfully identifying the bridge frequency. It is convinced that existing traffic on a bridge can enhance the measurement of the bridge frequencies from the passing vehicle despite the presence of road surface roughness.

For the second case, the same five sequential vehicles passing through the bridge as for the first



(a) (b)

Fig. 10 Responses of test vehicle passing though the bridge with surface roughness ($v = 10$ m/s): (a) acceleration response, (b) spectrum



(a) (b)

Fig. 11 Responses of test vehicle passing though the bridge with surface roughness ($v = 2.5$ m/s): (a) acceleration response, (b) spectrum

case are considered except that they are allowed to moving at the following three speeds: 2.5, 5, and 10 m/s. Figs. 9, 10, and 11 show the responses and corresponding spectra of the passing test vehicle at the speed of 5, 10, and 2.5 m/s, respectively.

It is observed from Figs. 9(a), 10(a), and 11(a) that, as the vehicle speed varies, the maximum response does not change a lot, usually being around 2 m/s^2. But the frequency distribution changes greatly. In Figs. 11(b), 9(b), and 10(b), as the vehicle speed increases from 2.5 m/s, 5 m/s, to 10 m/s, the vibration energy of the test vehicle tends to concentrate more on the bridge frequency component than on the vehicle frequency component. As a result, one may conclude that to raise the speed of existing traffic is also helpful for enhancing the extraction of the bridge frequencies from a passing vehicle.

6. Conclusions

In this study, the effect of road surface roughness on the indirect approach for measuring the bridge frequencies from a passing vehicle is studied through the finite element simulations. By comparing the result for the vehicle moving over a rigid ground with smooth surface with that over a bridge without rough surface, it is shown that the presence of surface roughness may result in much larger amplitudes for the vehicle frequency component than those for the bridge frequency components induced by the passing vehicle. Such a result may have negative consequence on the extraction of bridge frequencies from the passing vehicle, making the indirect approach not really workable. Moreover, the amplitude of the vehicle response becomes larger as the condition of road surface roughness gets poorer.

However, it is illustrated that, despite of the presence of surface roughness, the bridge frequencies can still be extracted from the dynamic responses of a passing vehicle with the aid of the following two ways: one is to amplify the amplitude of the bridge frequency components by introducing multiple passing vehicles and the other is to make the vibration energy more concentrated in the bridge frequency components by raising the traveling speed of the accompanying vehicles.

Reference

Chang, K.C. and Yang. Y.B. (2007), "Field tests for extracting bridge frequencies from the acceleration responses of a passing vehicle", *Proceedings of the Twentieth KKCNN Symposium on Civil Engineering*, 1-4, Jeju, Korea.

ISO 8608 (1995), *Mechanical vibration-road surface profiles-reporting of measured data*, ISO.

Lin, C.W. and Yang, Y.B. (2005), "Use of a passing vehicle to scan the fundamental bridge frequencies: an experimental verification", *Eng. Struct*., **27**, 1865-1878.

Yang, Y.B. and Lin, C.W. (2005), "Vehicle-bridge interaction dynamics and potential applications", *J. Sound Vib*., **284**, 205-226.

Yang, Y.B., Lin, C.W. and Yau, J.D. (2004a), "Extracting bridge frequencies from the dynamic response of a passing vehicle", *J. Sound Vib*., **272**, 471-493.

Yang, Y.B. and Chang, K.C. (2009), "Extracting the bridge frequencies indirectly from a passing vehicle: parametric study", *Eng. Struct*., **31**, 2448-2459.

Yang, Y.B. and Yau, J.D. (1997), "Vehicle-bridge interaction element for dynamic analysis", *J. Struct. Eng. - ASCE*, **123**(11), 1512-1518. (Errata: **124**(4), 479).

Yang, Y.B., Yau, J.D. and Wu, Y.S. (2004b), *Vehicle-bridge interaction dynamics-with applications to high-speed railways*, World Scientific, Singapore, 530.

Yau, J.D. (2009), "Vehicle/bridge interactions of a rail suspension bridge considering support movements", *Interact. Multiscale Mech.*, **2**(3), 381-396.