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The use of an instrumented vehicle in a wavelet based damage detection approach for bridge structures

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ABSTRACT: Periodic monitoring of structures such as bridges is necessary as their condition can deteriorate due to environmental conditions and ageing, causing the bridge to become unsafe. This monitoring - so called Structural Health Monitoring (SHM) - can give an early warning if a bridge becomes unsafe. This paper investigates an alternative wavelet-based approach for the monitoring of bridge structures which consists of the use of a vehicle fitted with accelerometers on its axles. A simplified vehicle-bridge interaction model is used in theoretical simulations to examine the effectiveness of the approach in detecting damage in the bridge. The accelerations of the vehicle are processed using a continuous wavelet transform, allowing a time-frequency analysis to be performed. This enables the identification of both the existence and location of damage from the vehicle response. Based on this analysis, a damage index is established. A parametric study is carried out to investigate the effect of parameters such as the bridge span length, vehicle speed, vehicle mass, damage level, signal noise level and road surface roughness on the accuracy of results. In addition, a laboratory experiment is carried out to validate the results of the theoretical analysis and assess the ability of the approach to detect changes in the bridge response.

1 INTRODUCTION

The deterioration of bridge structures due to factors such as environmental conditions and ageing is of concern for transport authorities worldwide as it raises issues of safety, maintenance and economical resource allocation. Vibration based structural health monitoring (SHM) techniques (Carden & Fanning 2004) have been developed in recent years for this purpose and can be effective as part of maintenance strategies in providing a warning if a bridge's condition deteriorates. However, they usually require direct installations on the bridge which can be costly and labour intensive. To address this drawback, indirect vibration-based approaches utilising the response of a vehicle passing over a bridge have been proposed which aim to reduce the need for direct installations thus providing a more efficient and low-cost alternative. This paper investigates such an approach for the periodic monitoring of bridge structures in theoretical simulations and a laboratory experiment. It is wavelet-based, consisting of the use of a vehicle instrumented with accelerometers and aims to detect changes in the vehicle response corresponding to variations in the bridge condition, i.e., damage.

The feasibility of using this type of indirect approach to extract bridge properties such as frequency and changes in damping from the acceleration response of a passing vehicle has been verified theoretically by analyzing the spectra of the vehicle accelerations (Yang et al. 2004, McGetrick et al. 2009, Yang & Chang 2009, Keenahan et al. 2012). Experimental investigations have been carried out which validate the theoretical results (Lin & Yang 2005, Kim et al. 2011) while field trials have taken place which investigate similar indirect bridge monitoring approaches (González et al. 2008) highlighting that low vehicle speeds and sufficiently high dynamic excitation of the bridge are required for successful implementation of this approach due to the relatively high influence of road roughness on the vehicle response. Also, bridge condition assessment techniques using novel algorithms to extract properties such as bridge stiffness and damping from vehicle accelerations are found to have low sensitivity to vehicle speed, signal noise, road roughness and modeling errors (Bu et al. 2006, González et al. 2012).

Wavelet theory allows a signal to be analysed in both time and frequency domains simultaneously hence the popularity of its usage in damage identification applications is increasing. Hester & González (2011) provide examples demonstrating the capacity of the wavelet transform to capture time-frequency information while Reda Taha et al. (2006) discuss the use of wavelets in SHM applications. The potential of continuous wavelet transforms (CWTs) to be used in statistical pattern recognition approaches for structural damage detection is illustrated by Nair & Kiremidjian (2009). Their use has also been extended to numerical investigations of indirect approaches which aim to identify localized damage within a bridge from the wavelet transform of vehicle displacements (Nguyen & Tran 2010, Khorram et al. 2012) and accelerations (McGetrick & Kim 2013) It is found that low speeds are beneficial for this type of approach and it can be more effective than using fixed sensors on the bridge.

This paper aims to extend the analysis carried out by McGetrick & Kim (2013) to other test conditions. For this investigation, a vehicle-bridge interaction (VBI) model is created and used for simulations in MATLAB to investigate the effectiveness of the wavelet-based indirect approach in detecting damage in a bridge. A time-frequency analysis is carried out in order to identify the existence and location of damage from the vehicle accelerations, which are processed using a Morlet CWT and a damage index is established based on this analysis. Bridge span length, vehicle mass and speed, damage level, road roughness and signal noise level are varied in simulations to investigate the effect on the accuracy of results. In an experimental investigation carried out to validate theoretical results, a scaled VBI model is utilized, consisting of a scaled two-axle vehicle and a simply supported steel beam incorporating a road profile.

2 MODELLING & SCENARIOS

2.1 Theoretical vehicle-bridge interaction model

A coupled VBI model described by McGetrick et al. (2013) is used in theoretical simulations (Figure 1). It consists of a 4 degree of freedom half-car model crossing over a finite element (FE) beam at constant speed; they are coupled at their points of contact. González (2010) provides a comprehensive review of similar coupled VBI models. The body and axle masses of the vehicle are m_s = 16200 kg, $m_{u,1}$ = 700 kg and $m_{u,2}$ = 1100kg respectively. The suspension and tire spring linear stiffness coefficients for axle 1 are $K_{s,1} = 4 \times 10^5$ N/m and $K_{t,1} = 1.75 \times 10^6$ N/m respectively while the corresponding values for axle 2 are $K_{s,2} = 1 \times 10^6$ N/m and $K_{t,2} = 3.5 \times 10^6$ N/m respectively. The suspension viscous damping coefficients are $C_{s,1} = 10 \times 10^3$ Ns/m and $C_{s,2} = 20 \times 10^3$ Ns/m. The sprung mass moment of inertia, I_s, is 93457 kgm^2. The centre of gravity, o, is located at the vehicle's midpoint thus $D_1=D_2=2.375$ m. Finally, the vehicle's frequencies of vibration are $f_{v,1}$ = 1 Hz, $f_{v,2}$ = 1.6 Hz, $f_{v,3}$ = 8.8 Hz and $f_{v,4}$ = 10.2 Hz corresponding to body bounce, body pitch and the hop of axles 1 and 2 respectively. The properties of the bridge spans used in simulations are given in Table 1. The coupled system is solved using the Wilson-theta integration scheme (Tedesco et al. 1999). A sampling frequency of 100 Hz is used in simulations. To damage the beam, percentage stiffness reductions are applied to individual elements, representing localized damage within the bridge. Acceleration measurements, $\ddot{y}_{s,i}$, are recorded above the axles as indicated in Figure 1.

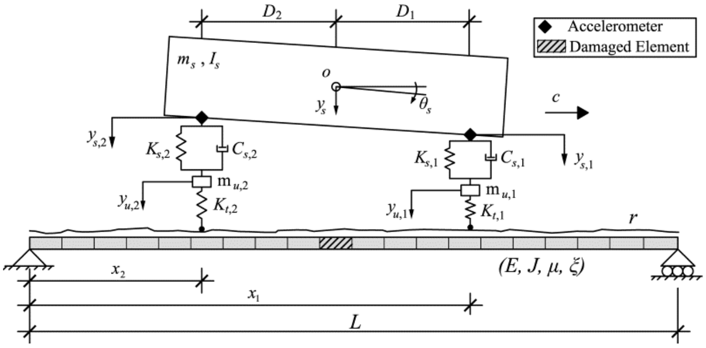

Figure 1.Vehicle-bridge interaction model.

Table 1 Finite element beam properties

Span Length, L (m)	Intact Element Stiffness, EJ (N m^2)	Mass per unit length, μ (kg/m)	Damping (%)	1st natural frequency of vibration, $f_{b,1}$(Hz)
15	1.846×10^{10}	28 125	3	5.66
25	4.865×10^{10}	18 358	3	4.09
35	1.196×10^{11}	21 752	3	3.01

2.2 *Experimental model*

The experimental setup is shown in Figure 2. A scaled two–axle vehicle with axle spacing of 0.4 m was fitted with 2 accelerometers, located at axle centres to monitor bounce motion. A wireless router and data logger allowed accelerations to be recorded remotely. The vehicle's speed was maintained constant by an electronic controller; each bridge crossing was repeated 5 times. Three speeds were adopted; S1 = 0.93 m/s, S2 = 1.16 m/s and S3 = 1.63 m/s. Two vehicles were used, V1 and V2, of masses 21.6 kg and 25.8 kg respectively. Their bounce frequencies were both 2.93 Hz while pitch frequencies were 3.9 Hz and 3.7 Hz respectively. The scaled bridge model was a simply supported steel beam with span, L_{exp} = 5.4 m and incorporated a scaled road surface profile. It had frequency $f_{b,exp}$ = 2.6 Hz, mass per unit length, μ_{exp} = 52 kg/m and stiffness, EJ_{exp} = 120,700 N m^2. It was fitted with accelerometers and displacement transducers at mid-span and quarter points to measure its response during vehicle crossings. For the experiment, damage was applied via 0.7 m long rectangular saw-cuts in the beam's flanges between midspan and 3/8^{ths} of the span. Four scenarios were investigated: Intact, D1, D2 and D3 corresponding to no damage, 5 mm, 10 mm and 15 mm cuts respectively (Figure 2(c)). A sampling frequency of 100 Hz was used in the experiment.

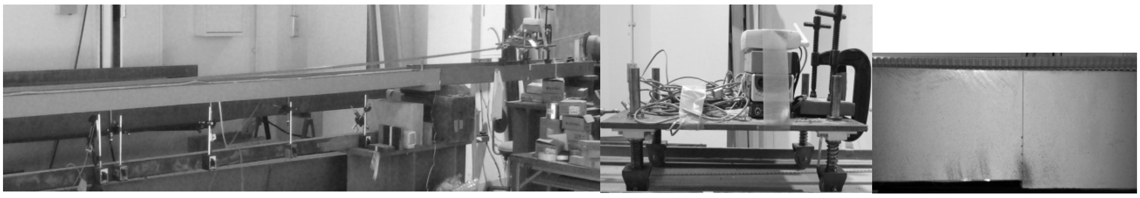
(a) Beam (b) Vehicle (c) Saw cut

Figure 2. Experimental setup.

2.3 *Continuous Morlet Wavelet transform and damage index*

The continuous wavelet transform (Mallat 1999) of a function $f(t) \epsilon L^2(\mathbf{R})$ is given as

$$Wf(a,b) = \int_{-\infty}^{\infty} f(t) \frac{1}{\sqrt{a}} \psi^{*}\left(\frac{t-b}{a}\right) dt \tag{1}$$

where * indicates the complex conjugate of the mother wavelet function, $\psi(t) \in L^2(\mathbf{R})$, which is given by Eq. 2,

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}} \psi\left(\frac{t-b}{a}\right) \tag{2}$$

The wavelet function is scaled by a and translated by b. The mother wavelet adopted for this investigation is the Morlet wavelet, as used by McGetrick & Kim (2013) and described by $\psi(t) = e^{-t^2/2}\cos(5t)$. It is a real valued symmetrical wavelet. Time localisation is an important criterion in order to detect damage location and it is found that the Morlet wavelet provides an appropriate balance between time and frequency resolution for this purpose. Therefore the Morlet CWT of vehicle acceleration responses is adopted as a damage sensitive feature.

2.3.1 Damage index

The CWTs of accelerations obtained in theoretical simulations and the experiment are analyzed in both time and frequency domains simultaneously for the purpose of damage detection. All acceleration signals are normalized using their standard deviations before applying the CWT. Peaks occurring in the *difference* between wavelet coefficients from healthy and damaged cases indicate the existence and location of damage. A damage index based on the maximum magnitude of these peaks at particular frequencies is established. It focuses on frequencies related to the vehicle as they are the most dominant in the VBI.

3 RESULTS DISCUSSION

3.1 Theoretical simulations

The aim of theoretical simulations is to investigate the effectiveness of the wavelet based indirect approach in identifying the existence and location of damage in a bridge for a range of parameters. Bridge span lengths of 15 m, 25 m and 35 m, vehicle speeds of 2 m/s, 5 m/s, 10 m/s and 20 m/s, vehicle masses of 9 tonnes and 18 tonnes, smooth profiles and a total number of 51 rough road profiles are tested in simulations. The effect of contaminating measurements with additive white Gaussian noise of signal-to-noise ratio (SNR) of 20 is also investigated. The damage level and location are also varied; stiffness reductions from 5% up to 20% are applied to an individual beam element at $L/2$ or $5L/8$. Results are presented in this section for measurements above axle 1 only; similar results were found for those above axle 2.

3.1.1 The Effect of Bridge Span Length

The effect of varying the bridge span length is shown in Figure 3; parallel vertical lines indicate the entry/exit time of the axle on the damaged beam element. It can be seen that for all spans, 5% damage at midspan is detected and located in the difference between damaged and healthy wavelet coefficients at peaks which correspond to the vehicle frequency of 1 Hz. As the span increases, the coefficient magnitudes increase and also, the time localization improves due to the longer time history of VBI available for analysis. This indicates that the approach may be more effective for longer spans provided the vehicle and bridge frequencies are not close.

3.1.2 The Effects of Vehicle Mass and Speed

Figure 4(a) shows that reducing the vehicle mass to 9 t improves damage localization compared to Figure 3(a) for the 18 t vehicle although the maximum coefficient does not change. This improvement is most likely due to the increase in vehicle frequency caused by the decrease in mass. However, the response at the bridge frequency increases also which may have a negative impact on locating damage for longer span bridges. For the 18 t vehicle as speed increases (Figure 4(b) and (c)), the maximum magnitude, time and frequency resolutions of the coefficients decrease due to shorter VBI time but the damage can still be detected and located. For 20 m/s, the damage is located despite the bridge and vehicle frequency peaks merging.

3.1.3 The Effects of Damage Level and Location

In Figure 5(a), the effect of varying the damage location can be observed; here, 5% damage is applied to an element at 5*L*/8. By comparing with Figure 3(a) it can be seen that the damage is detected at the new location with similar accuracy and coefficient magnitude. The effects of increasing the damage level at midspan to 10% and 20% are illustrated in Figure 5(b) and (c) respectively. The only significant effect observed is the increase of coefficient magnitudes with increasing damage. This suggests magnitudes may potentially be used to quantify damage.

3.1.4 The Effects of Signal Noise and Road Roughness

The results presented thus far have been for ideal conditions. In reality, the road surface will not be perfectly smooth and measurements may suffer from inaccuracies such as signal noise. Therefore in this section, results are presented from simulations in which noise (SNR=20) and a rough road surface were included separately.

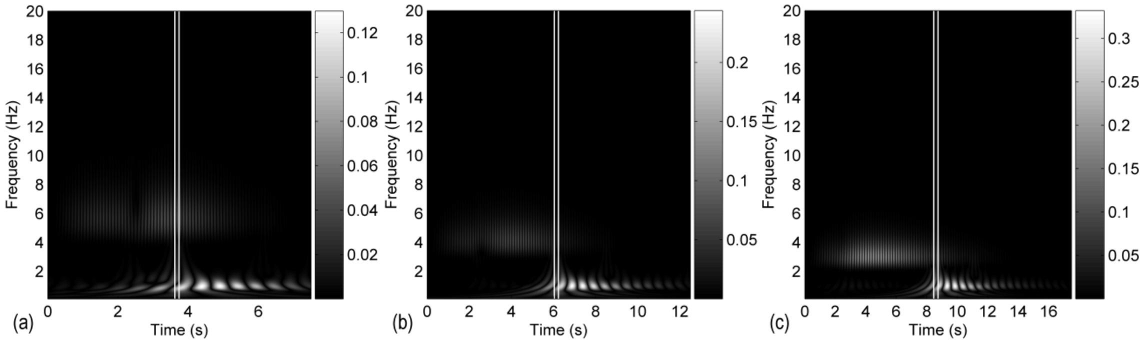

Figure 3. Difference between wavelet coefficients of accelerations above axle 1 on (a) 15 m span (b) 25 m span (c) 35 m span; speed is 2 m/s, damage level 5% at *L*/2, smooth road profile.

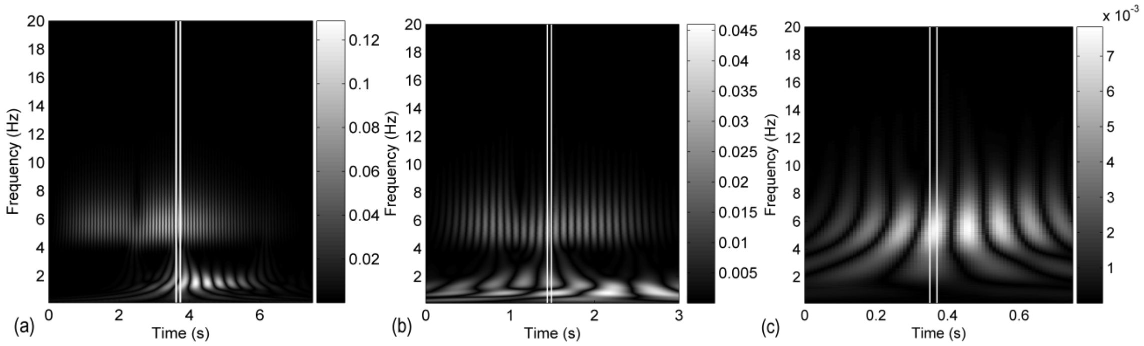

Figure 4. Difference between wavelet coefficients of accelerations above axle 1 for 15 m span (a) 9 t vehicle at 2 m/s (b) 18 t at 5 m/s (c) 18 t at 20 m/s; damage level 5% at *L*/2, smooth road profile.

Figure 6(a) shows results obtained using noise contaminated accelerations; these signals are low pass filtered below 8 Hz before being processed by the CWT as the main frequencies of interest are less than this. The damage can be located at the vehicle frequency in the presence of noise but is now more difficult to distinguish. Despite testing a range of 51 randomly generated 'very good' class A road profiles (ISO 1995) in simulations with no noise, it is found that as for the smooth profile, the damage can be detected in the vehicle response. This can be seen in the two examples given in Figure 6(b) and (c), although the magnitudes of the coefficients are much lower for the rough road profiles.

To illustrate the effectiveness of the approach overall for rough profiles, a damage index based on the maximum coefficient difference in the frequency range from 0.5 Hz to $(f_{v,1} + f_{b,1})/2$ is calculated and plotted in Figure 7(a) for all speeds and profiles tested. To allow comparison between the indices for all damage levels, they are standardized for each speed using their means and standard deviations. Indices for all speeds are grouped in Figure 7(a) according to the damage level and 1% damage is included here for comparison. It is clear from this figure that as the damage increases, so too does the selected damage index. This indicates that the index could be effective for both damage detection and quantification while it is not significantly affected by speed. Figure 7(b) summarizes the results for identifying damage location; damage level was found to have no effect hence only one level is shown here. The mean errors as percentages of the bridge span length are 15.8%, 30.1%, 21.6% and 3.2% for 2, 5, 10 and 20 m/s respectively. The identified location does not vary significantly with road profile. Here, the accuracy appears to be the best for 20 m/s which may be due to higher excitation of the bridge, or the poor resolution noted in Figure 4(c). Considering the poor resolution at this speed, it is expected that if the speed was increased further, the accuracy would decrease due to the shorter VBI time.

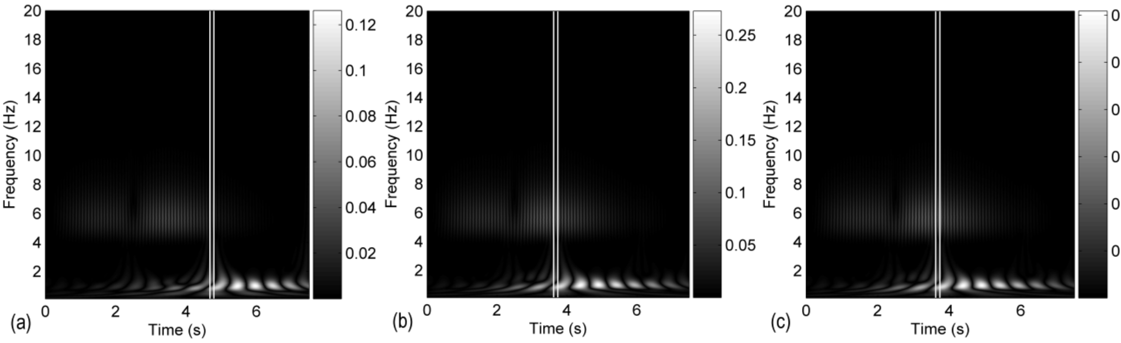

Figure 5. Difference between wavelet coefficients of accelerations above axle 1 of 18 t vehicle for 15 m span (a) 5% damage at 5*L*/8 (b) 10% damage at *L*/2 (c) 20% at *L*/2; speed is 2 m/s, smooth road profile.

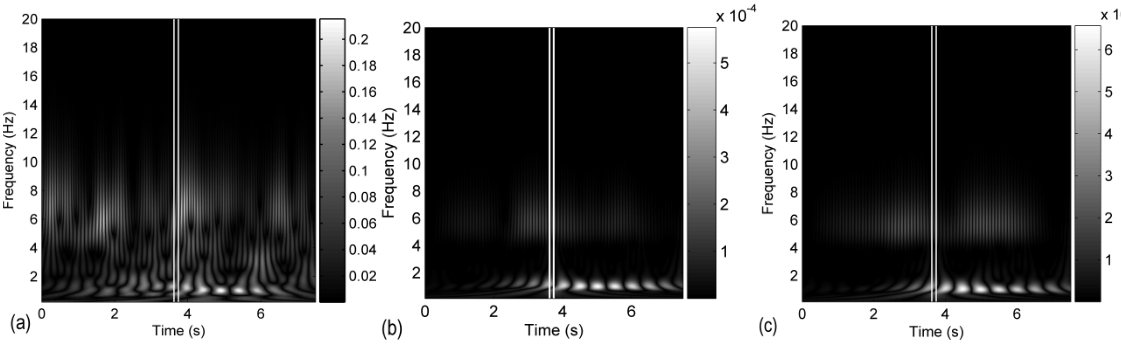

Figure 6. Difference between wavelet coefficients of accelerations above axle 1 of 18 t vehicle for 15 m span with 5% damage at *L*/2 (a) smooth profile with SNR = 20 (b) very good profile 1 (c) very good profile 2; speed is 2 m/s.

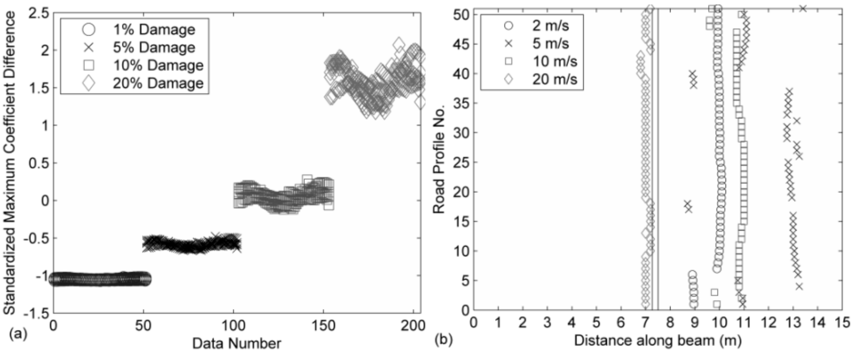

Figure 7 Identified damage (a) indices and (b) locations; 15 m span, damage at *L*/2, 51 class A profiles.

3.2 *Laboratory Experiment*

The results of the experiment are summarized in Figure 8 for axle 2 of the vehicle, which was found to be more accurate due to its frequency. Figure 8(a) shows an example of the difference between wavelet coefficients obtained for Intact and D3 scenarios; the largest peaks occur at the start and end of the time history at the vehicle frequency of 3.7 Hz however the damage location is detected at the bridge frequency of 2.6 Hz. Figure 8(b) and (c) show the damage indices calculated for all speeds, tests and damage scenarios for both vehicles. It is clear that the index is not as sensitive here as in simulations; D2 is difficult to distinguish from D1. However, D3 can be distinguished from D1 more easily. Speed is not found to have a significant effect.

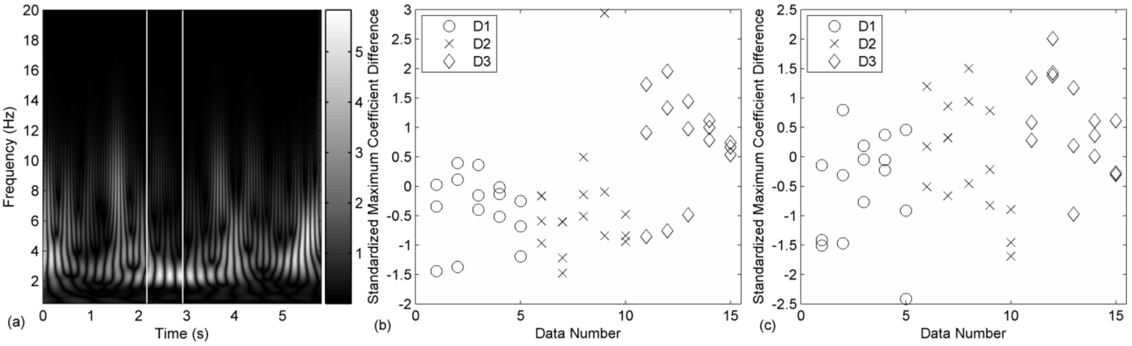

Figure 8 Experiment results (a) Difference between wavelet coefficients of accelerations above axle 2 for vehicle V2 and speed S1; Identified damage indices for (b) vehicle V1 and (c) V2 for all speeds and tests.

4 CONCLUSIONS

This paper investigates a wavelet-based approach for the monitoring of bridge structures which consists of the use of a vehicle instrumented with accelerometers on its axles. In theoretical simulations, it is found that the approach can detect and locate bridge damage more accurately for lower vehicle speeds and longer bridge spans due to time resolution. The damage is detected at the vehicle frequency response for smooth and rough road profiles but it is more difficult to locate in the presence of signal noise. A damage index based on the difference between wavelet coefficients of accelerations allows different levels of damage to be detected and distinguished from each other. However, in the laboratory experiment damage can be detected but it is found to be more difficult to distinguish between damage scenarios using this index. Overall, this investigation has illustrated the potential of this low-cost approach and highlighted conditions within which it can detect bridge damage with reasonable accuracy. Further work is required to address challenges associated with the real-world application of this approach.

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