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MONITORING BRIDGE DYNAMIC BEHAVIOUR USING AN INSTRUMENTED TWO AXLE VEHICLE

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Abstract
Highway structures such as bridges are subject to continuous degradation primarily due to ageing, loading and environmental factors. A rational transport policy must monitor and provide adequate maintenance to this infrastructure to guarantee the required levels of transport service and safety. Increasingly in recent years, bridges are being instrumented and monitored on an ongoing basis due to the implementation of Bridge Management Systems. This is very effective and provides a high level of protection to the public and early warning if the bridge becomes unsafe. However, the process can be expensive and time consuming, requiring the installation of sensors and data acquisition electronics on the bridge. This paper investigates the use of an instrumented 2-axle vehicle fitted with accelerometers to monitor the dynamic behaviour of a bridge network in a simple and cost-effective manner. A simplified half car-beam interaction model is used to simulate the passage of a vehicle over a bridge. This investigation involves the frequency domain analysis of the axle accelerations as the vehicle crosses the bridge. The spectrum of the acceleration record contains noise, vehicle, bridge and road frequency components. Therefore, the bridge dynamic behaviour is monitored in simulations for both smooth and rough road surfaces. The vehicle mass and axle spacing are varied in simulations along with bridge structural damping in order to analyse the sensitivity of the vehicle accelerations to a change in bridge properties. These vehicle accelerations can be obtained for different periods of time and serve as a useful tool to monitor the variation of bridge frequency and damping with time.

Keywords: Bridge, Monitoring, Transportation

1. Introduction

For widespread implementation of Bridge Management Systems, a large number of bridges must be instrumented and monitored. Given the very large number of bridges that are not instrumented, some alternative method is needed to detect any change in behaviour of the structure which may indicate some form of damage. This paper investigates the use of a vehicle fitted with accelerometers on its axles to monitor the dynamics of bridges. The frequency of a bridge may vary significantly during short periods of time as result of environmental conditions, but a change in bridge frequency over long periods of time may be a clear sign of deterioration. Damping has also been shown to be a damage sensitive parameter (Curadelli *et al*, 2008; Modena *et al*, 1999). This approach reduces the need for any equipment to be installed on the bridge and would allow the assessment of bridge condition to become a simplified and

considerably less time consuming process. It would bring about more efficient monitoring of the condition of existing bridges in a transport network while its development would enable maintenance to be undertaken at an earlier stage in degradation, which in general results in more economical repairs.

Yang *et al* (2004) theoretically verified the feasibility of extracting bridge dynamic parameters from the dynamic response of a vehicle passing over a bridge. The approach investigated by Yang *et al* employed a vehicle instrumented with accelerometers acting as a 'message carrier' of the dynamic properties of the bridge. The bridge was assumed to be a simply supported beam while a simplified sprung mass model represented the vehicle. The bridge natural frequency was extracted from the vehicle acceleration spectrum of the sprung mass and they found that the magnitude of the bridge natural frequency peak increased with vehicle speed but decreased with increasing bridge damping ratio.

Experimental investigations of this method have been carried out by Lin and Yang (2005) and González *et al* (2008). Lin and Yang validated the method in field tests using a two wheeled cart fitted with an accelerometer which was towed by a light two axle truck across a simply supported 30m span of a six span bridge. They found that the bridge frequency was easily identified at vehicle speeds less than 40 km/h (11.11m/s) but at higher speeds the bridge frequency becomes hidden by high frequency components from pavement roughness and cart structure. They also found that carrying out the field test while traffic was crossing the bridge had a beneficial effect as it increased the vehicle response.

The experimental analysis by González *et al* consisted of a field test on a main route near Oviedo, Northern Spain. A vehicle instrumented with accelerometers and GPS was driven over a long-span bridge (9 spans of lengths between 41 and 50 m, total length of 423.5 m) to obtain its frequencies. Their analysis of the technique also included a 3-D FEM vehicle-bridge interaction (VBI) model in which the method was tested numerically for various speeds, road roughness, damping levels and traffic conditions. They concluded that it is only feasible to extract the bridge frequency accurately from the dynamic response of the vehicle at low speeds and also when the bridge dynamic excitation is sufficiently high as the interference of road surface profile frequencies corrupt the spectrum and prevent the identification of the bridge natural frequency.

A theoretical investigation of the identification of bridge dynamic parameters using a 2-degree-of-freedom quarter-car model was carried out by McGetrick *et al* (2009). The aim of the investigation was to identify not only bridge frequencies of vibration but also a change in the bridge's structural damping. McGetrick *et al* conclude that the bridge's frequency of vibration and structural damping can be identified with ease from the dynamic response of the quarter car for a smooth road profile, while in the presence of a rough road profile the same properties become very difficult to identify.

González *et al* (2010) extended the analysis by McGetrick *et al* to a 4-degree-of-freedom half-car model and they found similar conclusions. Therefore, they noted that frequency matching between the axle hop of the vehicle and the natural frequency of the bridge is beneficial for the detection of that bridge frequency. The effect of a change in bridge damping on the vehicle response appeared reasonably small compared to the effect of a change in the road profile.

This paper builds upon the theoretical analysis carried out by González *et al*. The aim is to carry out a sensitivity study of some parameters that affect the dynamic response of the vehicle and as a result, the identification of the natural frequency of

vibration of the bridge and changes in structural damping. A VBI simulation model is created in MATLAB for this purpose. The spectra of accelerations of the front axle are obtained from the dynamic response of the half-car as it crosses the bridge. The dominant frequencies of vibration are extracted from the acceleration spectra and compared to the exact bridge or half-car frequencies. As González *et al* included a study of various bridge span lengths this paper focuses only on a 15 metre bridge span. Bridge structural damping is varied from 0% to 5% (in steps of 1%). 0% bridge damping is only a reference point, although some long-span bridges may exhibit damping ratios as low as 0.3%. The vehicle properties varied in simulations are axle spacing (3.75 and 4.45 metres) and gross vehicle weight (9 and 18 tonnes). Two road conditions are tested: smooth and ISO Class A. The results will indicate the conditions in which this method can be used to monitor bridge dynamic properties with a sufficient degree of accuracy.

2. Vehicle – Bridge Interaction Model

A theoretical half-car model is used to represent the behaviour of the vehicle. The model has 4-degrees-of-freedom which allows for axle hop, sprung mass bounce and sprung mass pitch rotation. The body of the vehicle is represented by the sprung mass, m_s, and the front and rear axle components are represented by unsprung masses, m_{u1} and m_{u2} respectively. The axle mass connects to the road surface via a spring of stiffness K_t, while the body mass is connected to the tyre by a spring of stiffness K_s in combination with a viscous damper of value C_s modelling the suspension. Tyre damping is assumed to be negligible and thus is omitted. The model also accounts for the sprung mass moment of inertia, I_s, and the distance of each axle to the vehicle's centre of gravity, i.e., D_1 and D_2 in Table 1. The centre of gravity of the vehicle is taken to be equidistant from each axle ($D_1 = D_2$), i.e., body weight equally distributed between axles. The half-car property values are listed in Table 1 and are based on values obtained from work by Harris *et al* (2007) and Cebon (1999).

Table 1 - Half car properties

Property	Unit	Symbol $i=1,2$	GVW = 9 tonnes		GVW = 18 tonnes	
			Model 1	Model 2	Model 3	Model 4
Body mass	kg	m_s	7600		16600	
Axle mass	kg	m_{ui}	1100		1100	
Suspension Stiffness	N/m	K_{si}	1×10^6		1×10^6	
Suspension Damping	Ns/m	C_{si}	10×10^3		10×10^3	
Tyre Stiffness	N/m	K_{ti}	3.5×10^6		3.5×10^6	
Moment of Inertia	kg m^2	I_s	26462	35043	61485	81423
Distance of axle *i* to centre of gravity	m	D_i	1.875	2.225	1.875	2.225
Axle hop frequency	Hz	f_{axle1}	10.27	10.27	10.21	10.22

The half-car travels at constant speed, c, over a simply supported Euler-Bernoulli beam which has constant cross section and mass per unit length, $\mu = 28125$ kg/m. It has span $L = 15$ metres, modulus of elasticity $E = 3.5 \times 10^{10}$ N/m^2, second moment of area $J = 0.5273$ m^4 and structural damping ξ which varies from 0% to 5%. The first natural frequency of the bridge, $f_{bridge1}$, is 5.66 Hz. Prior knowledge of this frequency is assumed here. In practice this can be obtained using a method described by Yang *et al* (2004), Lin and Yang (2005) and González *et al* (2008).

The simulation of the half-car crossing the beam is described by a system of coupled differential equations and is based on the approach proposed by Frýba (1999). The system of equations is solved using the Wilson-Theta integration scheme (Tedesco *et al*, 1999). The value of θ used is 1.420815.

3. Smooth Road Profile Results

The simulations in this section are performed using the VBI model outlined in Section 2 with a smooth road surface profile. The bridge structural damping is varied in the simulations along with the half-car mass and axle spacing. The exact frequencies of the bridge and half-car given in Section 2 will be compared to the frequencies in the spectra obtained from the vehicle accelerations. The scanning frequency used in all simulations is 8192 Hz.

3.1 Sensitivity of Vehicle Accelerations to Damping

An example of the power spectra of accelerations obtained from the front axle of the half-car as it crosses the 15 metre bridge are shown in Figure 1 for a vehicle velocity of 22m/s, 3.75m axle spacing and 18 tonne GVW. All simulated structural damping levels (0% to 5%) are represented on this figure. A clear peak is visible at 6 Hz which corresponds to the first natural frequency of the bridge, $f_{bridge1}$. The resolution of the acceleration spectrum is ± 0.25 Hz which causes a slight deviation between the spectrum peak and the dashed line representing the bridge frequency. The accuracy of this peak could be improved by driving the vehicle at a lower velocity to increase the number of measurements which would result in a higher frequency resolution.
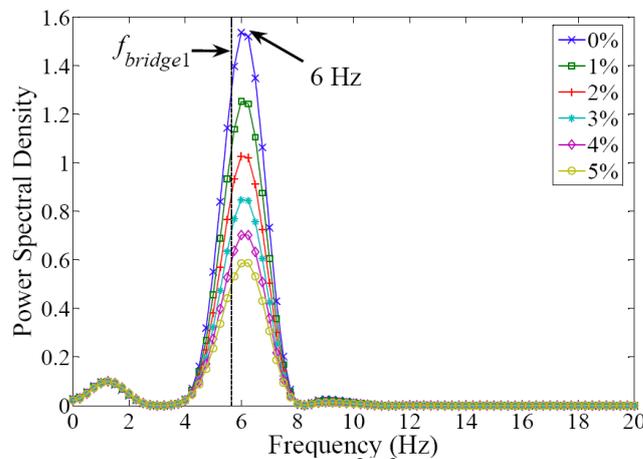

Figure 1 - Acceleration spectra (PSD in m^2/s^3) for front axle of 18 tonne half-car travelling over bridge with smooth road profile.

It can be seen that there is a decrease in Power Spectral Density (PSD) magnitude for increasing structural damping level at this peak. The sensitivity of this decrease to a 1% change in damping is greater for changes between lower levels of damping. For example, in this figure, for a change from 0% to 1% damping, the sensitivity of the PSD is 18.5% and from 1% to 2% the sensitivity is 18%. This sensitivity is obtained by calculating the difference between the PSD peaks and dividing it by the PSD peak magnitude at the lower damping level. This trend remained when other vehicle parameters were investigated.

The peak PSD is very sensitive to a change in damping when the bridge surface is smooth, which suggests that this peak could be used for periodic monitoring of bridge structural damping in these ideal conditions. It should be noted that results are shown for a vehicle velocity of 22m/s (80km/h) which corresponds to highway speeds, i.e. the instrumented vehicle would not cause traffic disruption while monitoring a bridge.

3.2 Effect of Vehicle Mass and Axle Spacing

Vehicle mass and axle spacing have been varied in simulations to investigate their effect on the ability to detect bridge frequency and structural damping from the acceleration spectrum. Results are shown in Figure 2 for a vehicle velocity of 22m/s. Only the spectra of axle accelerations for 2% and 3% damping are plotted, which is representative of the trend occurring for other damping levels. Figure 2(a) illustrates that as vehicle mass increases, the magnitude of the PSD at the bridge peak for a smooth profile increases which would improve sensitivity of the algorithm. Figure 2(b) illustrates that as axle spacing increases, the magnitude of the PSD at the bridge peak decreases which suggests that it is more favourable for the instrumented vehicle to have a shorter axle spacing. However, the relative sensitivities of the PSD peaks to changes in damping do not vary significantly with vehicle mass or axle spacing. For the 18t model with axle spacing of 3.75m, sensitivity between 2% and 3% is 17.5%, for the 9t model the equivalent value is 17.9% and for the 18t model with axle spacing of 4.45m the sensitivity is 17.2%.
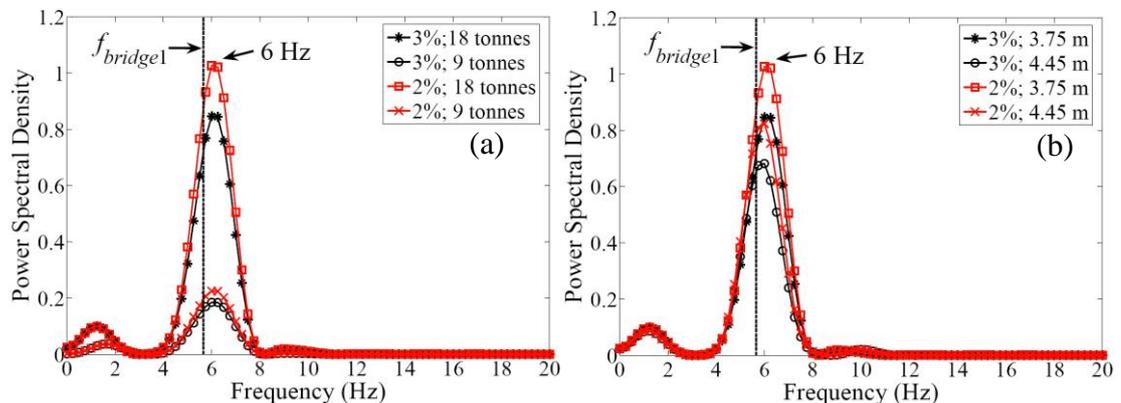

Figure 2 – Acceleration spectra (PSD in m^2/s^3) for front axle of half-car crossing bridge with smooth road profile varying: (a) vehicle mass (axle spacing is 3.75m) and (b) axle spacing (vehicle mass is 18t).

4. Rough Road Profile Results

A rough road profile is now included in the simulations. The road irregularities of this profile are randomly generated according to ISO (1995) for a 'very good' profile or road class 'A'. As for the smooth profile simulations, the structural damping is varied along with the half-car mass and axle spacing. The scanning frequency used in all simulations is 8192 Hz.

4.1 Sensitivity of Vehicle Accelerations to Damping

The spectra of accelerations obtained from the front axle of the half-car during the rough road profile simulation are shown in Figure 3(a) for a vehicle GVW of 18t with axle spacing 3.75m travelling at 22m/s. The resolution of the acceleration spectra is ± 0.25Hz. A large peak is visible in this figure which corresponds to the front axle hop frequency of the half-car, f_{axle1} (Table 1). However, there is no clear peak in the region around the first natural frequency of the 15 metre bridge. Also, it is not possible to distinguish between the different spectra for each damping level at the scale used in the figure. The rough road profile clearly interferes with the ability to detect bridge frequency and changes in structural damping and it governs the dynamic response of the vehicle. Comparing to the PSD magnitudes of Figure 1, the ISO class 'A' road profile produces a dynamic vehicle response which is approximately 200 times larger than the response due to a perfectly smooth road profile.

Despite the influence of the rough road profile and although it would be necessary to zoom into the figure to visualize the differences in PSDs, it is possible to capture changes in damping in the region of the first natural frequency of the bridge ($f_{bridge1}$). Thus, Figure 3(b) shows that by analysing the spectra at a frequency of 6Hz, which corresponds to the bridge peak obtained for a smooth profile in Figure 1, the PSD is still reasonably sensitive to changes in damping with an average sensitivity of 18%. The sensitivity to a 1% change in damping is greater for changes between lower levels of damping, a trend that was also observed in Section 3.1.
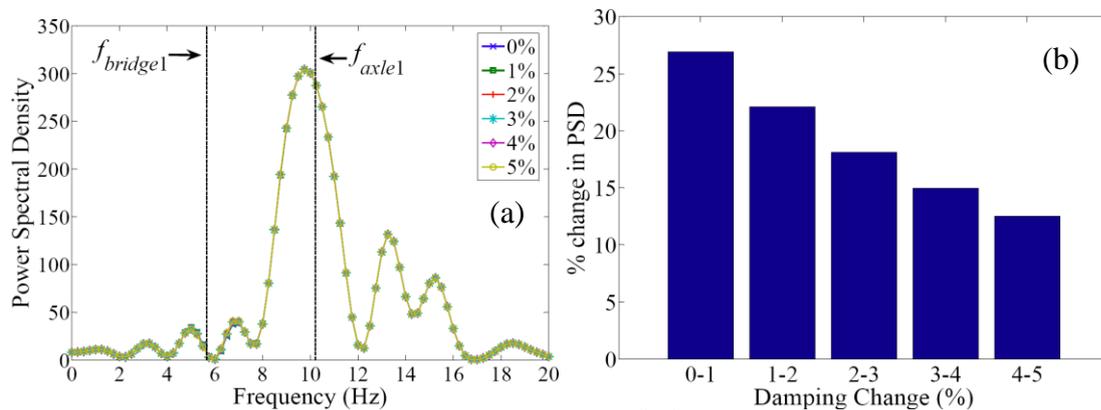

Figure 3 – (a) Acceleration spectra (PSD in m^2/s^3) and (b) Sensitivity of PSD of accelerations for front axle of 18 tonne half-car travelling over bridge with rough road profile.

4.2 Effect of Vehicle Mass and Axle Spacing

The relationships between vehicle mass and axle spacing and peak PSD magnitude in simulations with rough road profile are illustrated in Figure 4 for a vehicle velocity of 22m/s and two damping levels: 2% and 3%. Similarly to the smooth road profile, the peak PSD magnitude increases for increasing vehicle mass (Figure 4(a)). However,

Figure 4(b) illustrates that as axle spacing increases the magnitude of the peak PSD for a rough profile does not vary significantly.
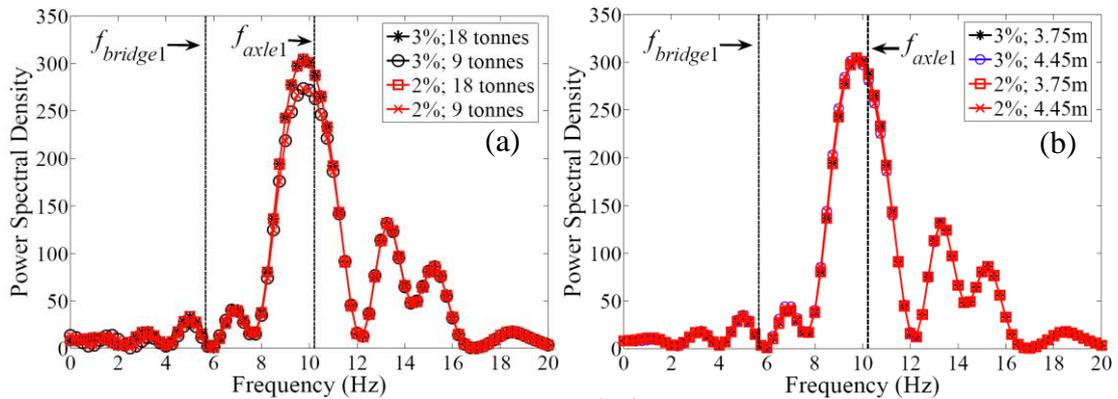

Figure 4 – Acceleration spectra (PSD in m^2/s^3) for front axle of half-car crossing bridge with rough road profile varying (a) vehicle mass (axle spacing is 3.75m) and (b) axle spacing (vehicle mass is 18t).

5. Conclusions

This paper has investigated the use of an instrumented two-axle vehicle to monitor the dynamic parameters of a bridge. The results show that it is possible to detect the bridge frequency from the vehicle vibration for smooth road profiles but it is more difficult to do so with rougher road profiles. This finding is in agreement with past studies. Using a heavier vehicle would increase the bridge deflection and thus increase the bridge influence on the vehicle vibration, improving results for a rough road profile. This paper has shown that the magnitude of PSD at the bridge frequency decreases with increasing bridge damping. This decrease is obtained and quantified easily for a smooth profile due to the presence of a dominant bridge frequency peak. For a rough road profile there is no such bridge peak but by analysing the spectrum in the region of the bridge frequency, changes in PSD exist due to changes in damping. The magnitude of the PSD for an axle of the half-car was found to increase for decreasing axle spacing for a smooth road profile and for increasing vehicle mass. Further study is required for the removal or reduction of the influence of the road profile roughness on the vehicle response to enable the development of an instrumented vehicle as an efficient low-cost method for monitoring bridge dynamic behaviour.

6. Acknowledgements

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