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Using Instrumented Vehicles to Detect Damage in Bridges

Eugene J. OBrien¹, Jennifer Keenahan¹, Patrick McGetrick², Arturo González¹
¹ UCD School of Civil, Structural and Environmental Engineering, Dublin 4, Ireland
² Kyoto University, Japan

email: eugene.obrien@ucd.ie, jennifer.nichoinneachain@ucdconnect.ie, mcgetrick@gmail.com, arturo.gonzalez@ucd.ie

ABSTRACT: This paper describes a ‘drive-by’ method of bridge inspection using an instrumented vehicle. Accelerometers on the vehicle are proposed as a means of detecting damage on the bridge in the time it takes for the vehicle to cross the bridge at full highway speed. For a perfectly smooth road profile, the method is shown to be feasible. Changes in bridge damping, which is an indicator of damage, are clearly visible in the acceleration signal of a quarter-car vehicle on a smooth road surface modelled using MatLab. When road profile is considered, the influence of changes in bridge damping on the vehicle acceleration signal is much less clear. However, when a half-car model is used on a road with a rough profile, it is again possible to detect changes in bridge damping, provided the vehicle has two identical axles.

KEYWORDS: Bridge; Damage; Damping; Dynamics; Vehicle Bridge Interaction; Damage detection; Drive-by.

1 INTRODUCTION

Loading, environmental factors and ageing result in the continuous degradation of highway structures such as bridges. Bridge management systems have been introduced in most developed countries, which are designed to provide a high level of protection and early warning if the bridge becomes unsafe as well as to facilitate a cost-effective distribution of the resources available for maintenance of the road infrastructure network. In most cases, bridges are inspected visually with an inspector looking for cracking and other indicators of damage. This is not only time consuming and expensive, but is unreliable as some forms of damage are not immediately visible.

In recent years, there has been a significant increase worldwide in the number of bridges being instrumented and monitored electronically [1], [2]. This process requires the installation of sensing equipment and data acquisition electronics in the bridge, which can be expensive. While it will undoubtedly become much more common in the future, it is unlikely in the medium term for the thousands of minor structures that make up the majority of the bridge stock in most countries.

This paper investigates the use of a vehicle fitted with accelerometers on its axles as an alternative method of ‘inspecting’ bridges. The vehicle drives over the bridge at full highway speed. The hypothesis is that damage in the bridge will manifest itself as small changes in the acceleration signals of the vehicle axles. This is based on the premise that bridge damage will result in significant changes in its structural damping, as has been reported by a number of authors [3], [4]. The bridge damping changes, in turn, cause changes in the vehicle acceleration signals.

So called ‘drive-by’ inspection of bridges is a relatively new field. [5] show that bridge frequencies can be extracted from the acceleration signal of a passing sprung mass. First natural frequency is a function of stiffness so damage that reduces stiffness will result in a reduction of bridge natural

frequency. [6] verified this approach experimentally using a heavy tractor towing an instrumented trailer. They got good results for speeds of up to 40 km/h but had difficulty at higher speeds.

[7] built a 3-dimensional vehicle-bridge dynamic interaction model to test the drive-by concept for a range of speeds, road roughnesses and damping levels. They also carried out field trials but concluded that the bridge frequency can only be determined with a drive-by system for lower speeds and when the excitation of the bridge is high.

A number of authors [8–10] report on the results of scale laboratory models to test the drive-by concept. These show promising results but the speeds are much slower than would be expected on a real bridge.

2 QUARTER-CAR MODEL SIMULATIONS

A theoretical quarter-car model is first used here to test the drive-by concept. The quarter-car (Figure 1) has two degrees-of-freedom, corresponding to the body bounce and axle hop motions.

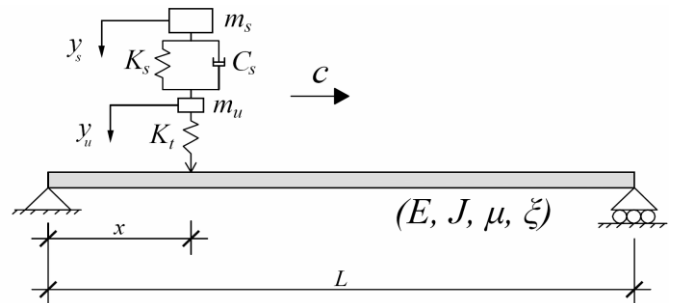


Figure 1. Theoretical quarter-car model.

The properties of this vehicle model are based on values obtained from work by [11] and [12]. Details are given by [13].

2.1 Vehicle-bridge dynamic interaction model

The equations of motion of the vehicle derive from the equilibrium of all forces and moments acting on the vehicle expressed in terms of the degree of freedom displacements, velocities and accelerations as shown in equation 1,

$$M_v \ddot{y}_v + C_v \dot{y}_v + K_v y_v = f_v \quad (1)$$

where M_v , C_v , and K_v are the mass, damping and stiffness matrices of the vehicle respectively. For this quarter car, the displacement vector, $y_v = \{y_s, y_u\}^T$, contains the sprung and unsprung displacements (see Figure 1). The excitation force vector, $f_v = \{0, -F_t\}^T$ contains the time varying interaction forces applied to the vehicle. The component, F_t , represents the dynamic interaction force at the base of the wheel as shown in equation 2,

$$F_t = K_t (y_u - w_v) \quad (2)$$

where w_v is the displacement of the base of the wheel. In general, this parameter represents the sum of the bridge displacement and road profile displacement under the wheel, r and w_b respectively.

Each vehicle model travels over a 15 m long simply supported Euler-Bernoulli beam. It consists of 20 discretised beam elements, each with two degrees of freedom and with a constant modulus of elasticity $E = 3.5 \times 10^{10}$ N/m². Therefore, the beam model has a total of $n = 42$ degrees of freedom. The bridge has a constant mass per unit length, $\mu = 28,125$ kg/m, and the second moment of area $J = 0.5273$ m⁴. The speed of the vehicle is maintained in simulations at 20 m/s. Prior knowledge of the first natural frequency of the bridge is assumed here at 5.6 Hz. The response of a discretised beam model to a series of moving time-varying forces is given by the system of equations that can be seen in equation 3,

$$M_b \ddot{w}_b + C_b \dot{w}_b + K_b w_b = N_b f_{int} \quad (3)$$

where M_b , C_b , and K_b are $(n \times n)$ global mass, damping and stiffness matrices respectively, w_b , \dot{w}_b , and \ddot{w}_b are the $(n \times 1)$ global vectors of nodal bridge displacements and rotations, their velocities and accelerations respectively, and $N_b f_{int}$ is the $(n \times 1)$ global vector of forces applied to the bridge nodes. The term, f_{int} represents the interaction force between the vehicle and the bridge and is described using the $(n_f \times 1)$ vector, as shown in equation 4,

$$f_{int} = \{P_1 + F_t\} \quad (4)$$

The matrix, N_b distributes the n_f applied interaction forces on beam elements to equivalent forces acting on the nodes. This location matrix can be used to calculate the bridge displacement under each wheel w_b using equation 5,

$$\{w_b\} = N_b^T w_b \quad (5)$$

Rayleigh damping is adopted here to model viscous damping. Hence, equation 6 shows,

$$C_b = \alpha M_b + \beta K_b \quad (6)$$

where α and β are constants.

The crossing of the vehicle model over each bridge is described by a system of coupled differential equations as proposed by [14]. The dynamic interaction between the

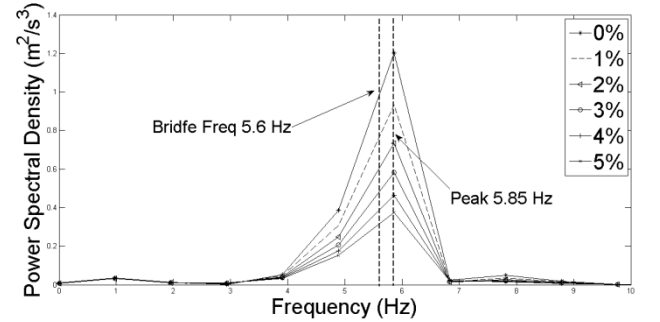
vehicle and the bridge is implemented in MatLab. The vehicle and the bridge are coupled at the tyre contact force, f_{int} . The coupled equation of motion is formulated as in equation 7,

$$M_g \ddot{u} + C_g \dot{u} + K_g u = F \quad (7)$$

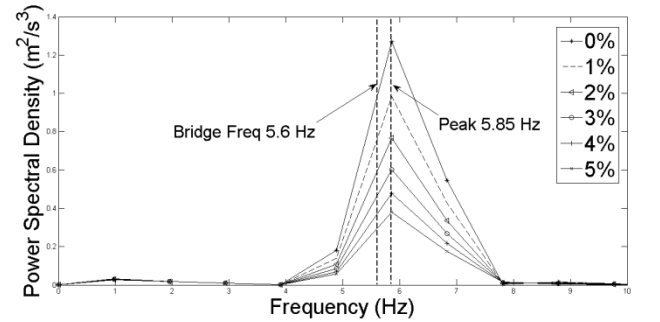
where M_g and C_g are the combined system mass and damping matrices respectively, K_g is the coupled time-varying system stiffness matrix and F is the system force vector. For the coupled system, $u = \{y_v, w_b\}^T$ is the displacement vector. The system of equations is solved using the Wilson-Theta integration scheme [15]. The value of θ used is 1.420815 [16].

2.2 Results of quarter-car simulations

The quarter-car model is first tested for a bridge with an idealised perfectly smooth profile, i.e., the displacement at the base of the wheel, w_v is exactly equal to the bridge displacement, w_b . The vehicle is simulated crossing six bridges that are identical except for differences in their damping coefficients, which range from 0% through to 5%. The bridges are excited by the passing of the vehicle along the span. The acceleration signals at the centre of the bridge are analysed and the Power Spectral Density is plotted in Figure 2(a). In each case, there is a peak in the acceleration spectrum at a frequency of 5.85 Hz. This is near the bridge first natural frequency of 5.6 Hz. The inaccuracy is due to the resolution of the spectra (± 0.96 Hz) which can be improved by driving the vehicle at a slower speed.



(a) Accelerations on bridge



(b) Accelerations on vehicle

Figure 2. Power spectral density of acceleration signals (perfectly smooth road profile)

There are clear differences in the signals when the damping coefficient of the bridge is changed. This confirms that, if an

accelerometer were installed at the centre of the bridge, it could be used to detect changes in damping and hence changes in its damage state. However, the drive-by concept seeks to detect damage in the bridge from the acceleration signals in the vehicle. Figure 2(b) shows these spectra and confirms that, in this case, an accelerometer on the passing vehicle is just as effective at detecting damage as an accelerometer attached to the bridge.

In the example of Figure 2, the road surface is perfectly smooth, clearly an unrealistic scenario. The simulations are repeated for the same quarter-car vehicle and bridge, but this time with a non-zero road surface profile. The road irregularities are randomly generated according to ISO [17]. The simulated road profile is of Class 'A' according to the ISO standard, as would be expected on a well maintained motorway surface. In such a case, the random road surface variations are far greater (± 4 mm) than the deformations due to bridge deflection. As a result, while the spectra for accelerations on the bridge are similar to Figure 2(b), the spectral densities are much greater for the quarter-car accelerations as seen in Figure 3.

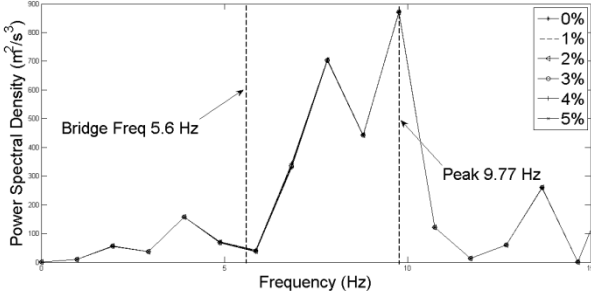


Figure 3. Power spectral density of acceleration signals (Class A road profile)

The excitation caused by the road surface profile variations is so great that there is no longer any visible difference in the six graphs plotted in Figure 3. All six spectra, regardless of damping level, are almost exactly the same. In this case, there is no longer a peak in spectral density at the bridge first natural frequency. The peaks that are shown relate to the road surface profile rather than to any property of the bridge.

3 HALF-CAR SIMULATIONS

A similar series of simulations is carried out with a more realistic half-car vehicle model. The half-car (Figure 4) has two degrees of freedom per axle with springs corresponding to suspension system and tyres. Unsprung masses correspond to the weights of the suspension system while the single sprung mass is shared between the axles, thereby allowing rocking as well as bouncing motions.

3.1 Vehicle-bridge model for half-car

The equations of motion of the half-car vehicle are similar in form to those of the quarter-car. Equation (1) still applies except that, this time, the vector, $y_v = \{y_s, \theta_s, y_{u1}, y_{u2}\}^T$ has four components corresponding to the four degrees of freedom of the vehicle. Similarly, the interaction force vector,

$f_v = \{0, 0, -F_{t,1}, -F_{t,2}\}^T$ contains four components for the half-car system. The term $F_{t,i}$ represents the dynamic interaction force at wheel i as displayed in equation 7,

$$F_{t,i} = K_{t,i} (y_{ui} - w_{v,i}) \quad i=1, 2 \quad (7)$$

$w_{v,i}$ is the total displacement under wheel i , made up of the road profile displacement and bridge displacement r_i and $w_{b,i}$ respectively.

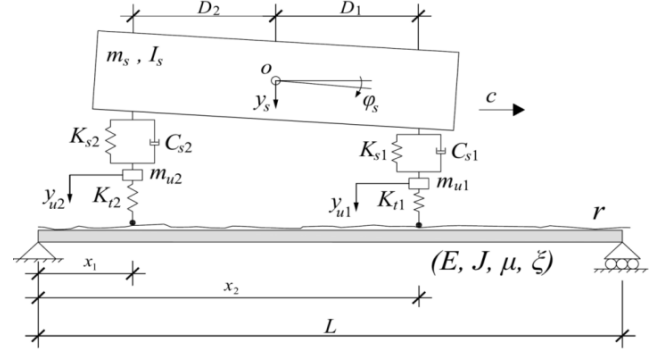


Figure 4. Half car model on bridge beam model

Equation (3) describes the beam model and applies for both quarter-car and half-car vehicles. However, for the half-car system, there are two interaction forces between the vehicle and the bridge with the result that f_{int} is a (2×1) vector as shown in equation 8,

$$f_{int} = \begin{Bmatrix} P_1 + F_{t,1} \\ P_2 + F_{t,2} \end{Bmatrix} \quad (8)$$

Similarly, N_b is an $(n \times 2)$ location matrix for the half-car vehicle that distributes the two applied interaction forces on beam elements to equivalent forces acting on the nodes.

3.2 Results of half-car simulations

As for the quarter-car simulations, in the half-car simulations bridge accelerations are found to change significantly as the damping of the bridge changes, as would be expected in response to certain kinds of damage. When the road surface is perfectly smooth, the spectra of vehicle accelerations also change in response to bridge damping changes. However, when there is a non-zero road profile, the vehicle acceleration spectra are similar in form to those of Figure 3. For all six cases of damping, the spectra are almost identical.

For a half-car with two identical axles, the excitation applied by a road surface profile is identical for each axle. Hence, the acceleration signals should be very similar, except for a phase difference due to the time difference between the two axles passing a given point. When the half car is crossing a bridge with a rough road profile, each axle is being excited by the same (time shifted) road profile but by a different part of the bridge. Hence, the time shifted *difference* between the accelerations in identical axles should be largely unaffected by road profile but strongly influenced by the bridge vibration.

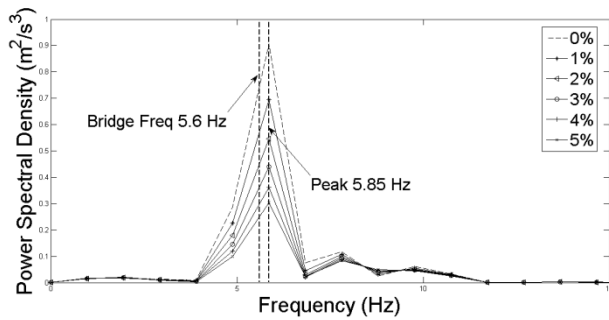


Figure 5. Power spectral density of difference between axle vibration signals

The feasibility of this approach is confirmed in Figure 5, which illustrates the power spectral densities of the time shifted differences between the axle vibration signals in the half car. There are clear differences between the six graphs, showing, once more, a strong dependence on bridge damping. The dominance of road profile influences on the quarter-car (Figure 3) is absent. It would appear that using a vehicle with identical axles and analysing the differences in the axle accelerations does have potential to be used as a drive-by damage detection system.

4 CONCLUSIONS

A 'drive-by' concept for bridge damage detection is tested in numerical simulations, i.e., the concept that acceleration signals in a vehicle passing over a bridge can be used to detect damage in the bridge itself. It is assumed that damage is correlated with bridge damping so that the goal is to use the passing vehicle to detect a change in bridge damping.

A quarter-car model shows that the passing vehicle can detect changes in damping when the road surface is perfectly smooth. However, even a good quality road surface is sufficient to completely change the vehicle excitation and to mask the influence of small changes in bridge properties.

A half-car model gives similar results to the quarter-car. However, the concept of using a half-car with two identical axles shows some promise. By subtracting the acceleration signals from subsequent axles, it is shown that the influence of the road surface profile can be removed and bridge damage can once more be detected.

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