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McGetrick, P. J., Kim, C-W., González, A., & OBrien, E. J. (2012). Dynamic axle force and road profile identification using a moving vehicle. In Proceedings of the 25th KKCNN Symposium on Civil Engineering (KKCNN 2012) (pp. 90-93)

Published in:
Proceedings of the 25th KKCNN Symposium on Civil Engineering (KKCNN 2012)

Document Version:
Peer reviewed version

Dynamic axle force and road profile identification using a moving vehicle

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ABSTRACT

The axle forces applied by a vehicle through its wheels are a critical part of the interaction between vehicles, pavements and bridges. Therefore, the minimisation of these forces is important in order to promote long pavement life spans and ensure that bridge loads are small. Moreover, as the road surface roughness affects the vehicle dynamic forces, the monitoring of pavements for highways and bridges is an important task. This paper presents a novel algorithm to identify these dynamic interaction forces which involves direct instrumentation of a vehicle with accelerometers. The ability of this approach to predict the pavement roughness is also presented. Moving force identification theory is applied to a vehicle model in theoretical simulations in order to obtain the interaction forces and pavement roughness from the measured accelerations. The method is tested for a range of bridge spans in simulations and the influence of road roughness level on the accuracy of the results is investigated. Finally, the challenge for the real-world problem is addressed in a laboratory experiment.

INTRODUCTION

It has been found that dynamic vehicle axle forces can increase the average road surface damage by up to four times compared to that caused by static axle forces alone (Cole and Cebon, 1992). Therefore, the minimisation of dynamic axle forces is important in order to promote long pavement life spans and ensure that bridge loads are small. In addition, as the road surface roughness influences these dynamic forces, it is generally accepted that the monitoring and maintenance of road profiles for highways and bridges is essential.

There are several existing methods for vehicle axle force identification. These include methods which use direct instrumentation and measurements of vehicle axles to obtain the force history; some examples are wheel hub transducers and air spring pressure transducer systems and a comprehensive review of these and other direct methods is provided by Davis and Bunker (2007). The accuracy of these methods can be quite good but they are also costly and in some cases difficult to install. As the dynamic axle forces are of particle importance for short to medium span bridges, in recent years there has been a significant amount of research carried out on methods utilising the moving force identification (MFI) technique, which is based on well-established general inverse problem theory, to identify the vehicle-bridge interaction forces indirectly via measurements on the bridge. Yu and Chan (2007) provide a comprehensive literature review of this research. Usually it is necessary to obtain measurements at a number of locations and the installation of the equipment and data acquisition electronics can be time consuming and costly, limiting the implementation of this type of approach.

Sayers and Karamihas (1998) discuss several existing methods for the measurement of road profiles such as static manual methods (dipstick walking profilometers, rod and level) and more efficient dynamic approaches, such as inertial profilometers, which can measure profile tracks at highway speeds. The typical inertial profilometer consists of a vehicle equipped with a height sensing device, such as a laser, which measures pavement elevations at regular intervals with the effects of vehicle dynamics removed from the elevation measurements via accelerometer(s). The method provides accurate, high resolution profile measurements but a drawback is the expense associated with laser-based technology. More recently, low cost approaches have been proposed which utilise vehicle accelerations in order to characterise or identify road profile heights (Harris et al 2010).

In this paper, the results of a novel algorithm for the identification of both dynamic vehicle forces and pavement profile heights are presented. MFI theory is applied to a vehicle model in order to identify the dynamic forces between the vehicle and the road and/or bridge. The methodology of the approach allows for the prediction of the pavement roughness. The low-cost approach presented in this paper has the benefit of only requiring the vehicle to be instrumented with accelerometers and eliminates the need for any equipment to be installed on the bridge. A coupled vehicle-bridge interaction (VBI) model is created

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in MATLAB to simulate ‘measured’ accelerations and the approach is numerically validated for bridge spans of 15, 25 and 35 metres, road profiles ranging from ISO class A (very good) to E (very poor) and a vehicle speed of 80 km/h (20 m/s). Further, measurements from a laboratory experiment are also analysed.

METHODOLOGY

Simulation Model

A coupled VBI model is used in simulations consisting of a 4 degree-of-freedom vehicle model and a finite-element (FE) beam, shown in Fig. 1. Only two on-vehicle acceleration measurement locations are utilised and these are indicated by the solid squares above the suspension of each axle in Fig. 1. Additive white gaussian noise with a signal-to-noise ratio (SNR) of 20 is added to these accelerations before they are used as input to the identification algorithm. A sampling frequency of 1000 Hz is used in all simulations.

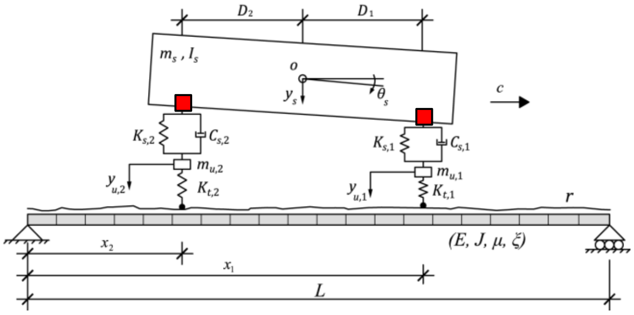

Fig. 1. Vehicle-bridge interaction model

Force Identification Algorithm

For the theoretical investigation, the algorithm’s inverse problem is formulated as a non-linear least squares minimisation of the difference between measured and theoretical vehicle accelerations, shown in Eq. (1). A state space formulation is used for the vehicle model and the *m*(= 2) acceleration measurements in vector $\mathbf{d}$ are related to the state space variables $\widehat{\mathbf{X}}$ using a selection matrix $\mathbf{Q}$: $\mathbf{d} = \mathbf{Q}\widehat{\mathbf{X}}$. First order Tikhonov regularisation is used to decrease errors due to ill-conditioning and the recursive least-squares problem is solved using the Dynamic Programming technique which has been utilised previously in force identification problems (González *et al.* 2008). This algorithm has been adapted from the MFI algorithm described in detail by González *et al.* (2008) and full details of the implementation discussed here can be found in McGetrick (2012).

$$Err(\widehat{\mathbf{X}}_k,\ \mathbf{r}_k)\ = \sum_{k=1}^{m}\big(\,\mathbf{d}_k - \mathbf{Q}\widehat{\mathbf{X}}_k\,,\mathbf{W}\big(\mathbf{d}_k - \mathbf{Q}\widehat{\mathbf{X}}_k\big)\,\big) + \ (\ \mathbf{r}_k\,,\mathbf{B}\mathbf{r}_k) \tag{1}$$

where $\mathbf{r}_k$ is a vector containing the derivative of the forces to be identified, $\mathbf{W}$ is an ($m \times m$) identity matrix and $\mathbf{B}$ is a regaularisation term. Also, $(\mathbf{x}\,,\mathbf{y})$ denotes the vector product of $\mathbf{x}$ and $\mathbf{y}$.

RESULTS AND DISCUSSION

Axle Force Identification

Fig. 2 shows an example of the dynamic axle forces identified from vehicle accelerations on the 25 metre bridge. It can be seen that the algorithm identifies the true forces accurately. However, due to the smoothing of the solution by the regularisation terms, the identified forces do not predict some of the higher frequency components of the true forces accurately. Nevertheless, the larger amplitude components of the true forces are predicted very well. These peaks are an important factor in relation to pavement and bridge damage as they can indicate specific locations in pavements where damage will be concentrated (Cole and Cebon 1992). Table 1 presents the Root Mean Square Error (RMSE) of the identified forces expressed as a percentage of the maximum absolute true force magnitude. The percentage RMSEs are given for each bridge span and road profile investigated. The errors observed here are primarily consequences of the presence of high frequency components in the true dynamic axle force history. However, the errors are primarily less than 10%. Similar accuracy is obtained for each bridge span and axle force. The values in this table suggest that the identified forces are not very sensitive to the road roughness as there are only slight variations in error as the roughness level increases.

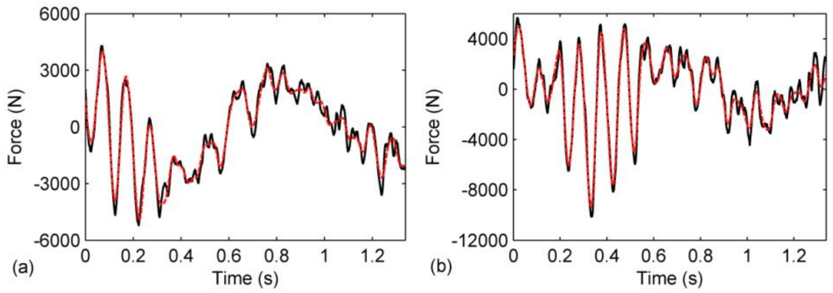

Fig. 2. Dynamic axle forces of vehicle crossing 25 m Class A Profile; (a) Axle 1 and (b) Axle 2. True forces (—) and forces identified using acceleration measurements (- - -).

Table 1 Percentage RMSE of identified dynamic axle forces

Profile Class	RMSE (%)					
	15 m Span		25 m Span		35 m Span	
	Axle 1	Axle 2	Axle 1	Axle 2	Axle 1	Axle 2
A (very good)	9.89	8.28	6.91	5.51	7.01	7.65
B (good)	8.11	8.38	9.86	8.7	6.36	7.34
C (average)	7.74	6.30	8.86	5.91	12.06	6.62
D (poor)	7.74	6.23	8.63	7.21	7.51	7.98
E (very poor)	9.51	5.99	10.12	8.22	7.51	8.97

Road Profile Heights

The results of road profile prediction for the class A profile are presented in Fig. 3. The measured acceleration data is obtained from a 100 m approach profile prior to the bridge. The prediction is very good overall. However, similar to the identified forces in the previous section, it can be seen that some of the very small amplitude higher frequency irregularities are not identified. This is particularly clear for the Power Spectral Density (PSD) of the profile heights shown in Fig. 3(b); it can be inferred that the predicted profiles are accurate for the frequency band between 0.01 cycles/m and 1 cycles/m approximately.

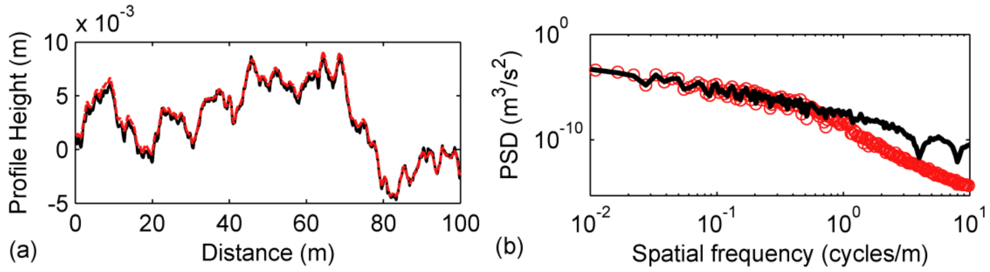

Fig. 3. Profile heights for ISO class A profile identified using accelerations (a) True (—) and identified (- - -) profiles under wheel 1. (b) Corresponding PSD of true (—) and identified (○) profiles.

Fig. 4 shows the results of profile prediction for the class C profile. The accuracy is similar to that for the class A profile. However, low frequency, long wavelength error has manifested itself as a shifted estimate for the road profile here. This type of error can be attributed to the acceleration measurements' poor sensitivity to lower frequency responses approaching the static frequency at 0 Hz. The identification was repeated using vehicle displacements as the input and the corresponding results are given in Fig. 5, showing that the use of displacements can overcome this shift and improve accuracy at lower frequencies.

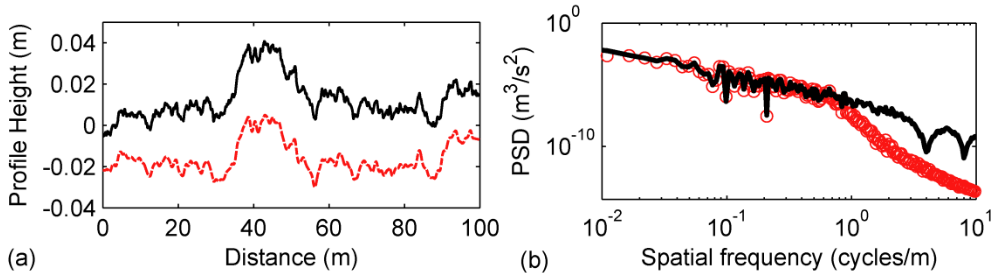

Fig. 4. Profile heights for ISO class C profile identified using accelerations (a) True (—) and identified (- - -) profiles under wheel 2. (b) Corresponding PSD of true (—) and identified (○) profiles.

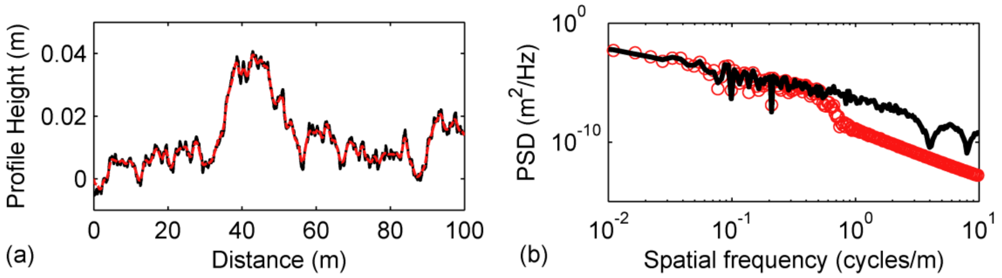

Fig. 5. Profile heights for ISO Class C profile identified using displacements (a) True (—) and identified (- - -) profiles under wheel 2. (b) Corresponding PSD of true (—) and identified (○) profiles.

The IRI values of all profiles predicted using acceleration measurements are presented in Table 2. The percentage errors are also tabulated. Results for the profile under wheel 2 are more accurate. The errors are all less than 10% and underestimate the IRI values. This relates to the poor estimation of higher frequency components of the road profile.

Table 2 Predicted IRI and percentage errors of identified road profile heights

Profile Class	$IRI_{1st\ profile}$ (m/km)		$IRI_{2nd\ profile}$ (m/km)	
	Predicted	% Error	Predicted	% Error
A	1.19	6.3	1.2	4.8
B	3.73	5.6	3.83	4.5
C	4.2	8.1	4.26	6.8
D	10	7.8	10.01	6.1
E	25.93	9.1	26.46	6

Experimental Results

In a laboratory experiment, the approach was applied to the accelerations responses of a scaled vehicle model crossing a scaled artificial road profile along a 5.4 metre steel beam. It was found that the axle forces were identified accurately however the initial conditions of the vehicle severely affected the accuracy of the algorithm's road profile identification. The experimental configuration and design was not ideal for its validation; all degrees of freedom were measured which resulted in a well-conditioned problem thus regularisation was unnecessary. In a real field experiment scenario, this approach is more effective as it is only feasible to obtain a limited number of measurements.

CONCLUSIONS

This paper presents the results of novel algorithm which utilizes MFI theory for the identification of dynamic axle forces and road profile heights from a vehicle's acceleration response. In a theoretical investigation, it was found that the algorithm identified the vehicle's dynamic axle forces as it crossed different bridge spans with reasonable accuracy. The identified forces were found to be insensitive to road roughness. The algorithm identified road profile heights of varying roughness quite accurately also, with an average IRI error of 6.5%. In a laboratory experiment, only the axle forces were identified accurately. However, overall these results illustrate the potential of this approach to be developed and implemented as a low-cost tool for identifying dynamic vehicle axle forces and the condition monitoring of pavements.

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