RAILWAY TRACK MONITORING USING DRIVE-BY MEASUREMENTS

Abdollah Malekjafarian[1], Eugene J. OBrien[1] and Daniel Cantero[2]

[1] *School of Civil Engineering, University College Dublin, Ireland*

[2] *NTNU Norwegian University of Science and Technology, Trondheim, Norway*

ABSTRACT

This paper presents the possibility of detecting considerable changes in track stiffness using the measurements from a laser vibrometer installed on a passing train. A numerical model of a two-dimensional train-track system is implemented in Matlab using the finite element method. The loss of stiffness in the track is modeled by reducing the stiffness of the sub-ballast layer of the track at specified points. The instantaneous velocity of the rail under the train is measured using four laser vibrometers mounted on the train. The simulations show that a change in the sub-ballast stiffness of the track can be detected and located from the drive-by measurements.

Keywords: Railway, Track monitoring, Drive-by, Train-track interaction.

1. INTRODUCTION

Railways play a key role in transport infrastructure. It is essential to monitor railway track properties to ensure the safety and comfort levels of railway networks and to optimise maintenance planning. Track stiffness is a critical parameter that may vary along the rail. A significant change in the railway track stiffness may indicate a fault either in the components of the track (sleepers, pads, etc.), or the ballast bed under it. The common methods for identifying the track stiffness are visual inspection, using stationary equipment or specialized (and expensive) track recording vehicles. These methods require track possession and are expensive to operate. The concept of installing sensors on a train in regular service (drive-by measurements) has been recently proposed for monitoring track stiffness. Drive-by measurements have been used by many researchers for road pavement (Flintsch et al., 2012) and bridge health monitoring (Malekjafarian et al., 2015, Malekjafarian and OBrien, 2017). In the context of road pavement monitoring, using a Traffic Speed Deflectometer (TSD) is one of the latest methods in use. The TSD is a vehicle instrumented with laser vibrometers which is used to measure the deflection ‘basin’ in a pavement, that is, the depression in the road pavement under a heavy axle as it passes. In the context of railway, an in-service train is instrumented with sensors and used to infer the track properties. This method has the potential to reduce the monitoring cost and provide more up-to-date results. Acceleration measurements are used for railway track monitoring using in-service train measurements (Bocciolone et al., 2007, Molodova et al., 2011, Lederman et al., 2017a). The sensors are usually installed on the train axle box and the responses are measured continuously. Real et al. (2011)

propose a method using Fourier transform for finding the rail irregularities using the vertical acceleration measurements on a passing train. OBrien et al. (2015) propose a method for determining vertical alignment of railway track from indirect measurements using an optimization algorithm. In this method, the track profile is estimated and deterioration in the track can be detected as changes in the profile. Cantero and Basu (2015) use wavelet transform of acceleration response of a passing train for railway track damage detection. Lederman et al. (2017a) use energy of acceleration responses of an operational train for track monitoring. In another study (Lederman et al., 2017b), they propose a novel analysis technique for track monitoring that exploits the sparsity inherent in train-vibration data. They use two-year real measurements data and show that track changes can be detected.

In this paper, four laser vibrometers are installed on a moving train, under the first axle which is inspired by the TSD concept. A numerical model of train-track interaction is implemented using finite element method. Four laser vibrometers are assumed to be installed under the first axle to measure the rail velocities. The stiffness of the sub-ballast layer at some points are reduced using a specified track stiffness profile. It is demonstrated that the rail velocities show the slopes of the rail deflections. The sub-ballast layer stiffness changes are detected using the instantaneous velocities.

2. NUMERICAL MODELLING OF TRAIN TRACK INTERACTION

A train-track interaction model described by Cantero et al. (2015) is developed in this paper. The train is modelled as a 2-dimensional car vehicle which is shown in Fig. 1. It consists of 10 DOFs including 4 wheelsets (vertical translation only), 2 bogies (vertical translation and rotation about each centre of gravity) and the main body (vertical translation and rotation). In this model, m_w represents the masses of the wheelsets, m_b and I_b represent the bogies mass and moment of inertia, m_v and J_v define the mass and moment of inertia. The primary suspension systems consisting of springs, k_p, and viscous dampers, c_p, connect the wheelsets to the bogies. The secondary suspension system consisting spring, k_s, and a viscous damper, c_s, connects the bogies to the main body. The vehicle properties are given in Table 1 (Goicolea 2014).

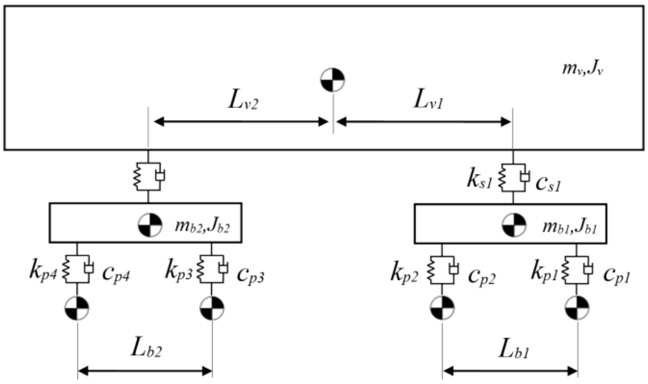

Figure 1: The train model.

Table 1: Properties of the train.

Property	Unit	Value
Wheelset mass	kg	1 800
Bogie mass	kg	3 500
Car body mass	kg	47 800
Moment of inertia of bogie	kg.m2	1 715
Moment of inertia of main body	kg.m2	1.96×106
Primary suspension stiffness	N/m	2.4×106
Secondary suspension stiffness	N/m	0.7×106
Primary suspension damping	Ns/m	20×103
Secondary suspension damping	Ns/m	40×103
Distance between car body centre of mass and bogie pivot	m	8.6875
Distance between axles	m	2.5

Fig. 2 shows the track model consisting of a beam supported on a 3-layer sprung mass system representing a sleeper, pad and ballast support system (Zhai et al. 1996, 2004, Lu et al. 2008, Lei and Zhang 2010, Nguyen et al. 2014). Track supports are spaced at a regular interval, L_s, representing the spacing between the sleepers. The rail is modelled as a finite element Euler-Bernoulli beam with two beam elements per sleeper spacing. The track properties are given in Table 2. In this study, the track consists of 1800 sleepers. A perfectly smooth track profile is considered in this study.

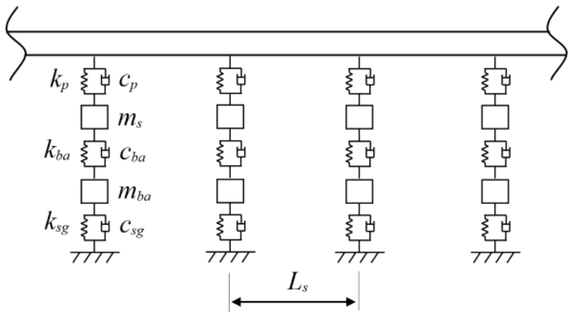

Figure 2: The track model.

The vehicle and track subsystems are combined at the wheelsets to form a coupled vehicle-track interaction model. The equations of motion for the coupled vehicle-track model are defined by a set of second order differential equations. The equations of motion are solved using the Wilson-θ numerical integration scheme (Bathe and Wilson 1976, Tedesco et al. 1999). A value of θ = 1.420815 is used to ensure unconditional stability of the algorithm (Weaver and Johnston 1987). The model is implemented in Matlab.

Table 2: Properties of the track.

Property	Unit	Value
Elastic modulus of rail	N/m2	2.059×1011
Rail cross-sectional area	m2	7.69×10-3
Rail second moment of area	m4	3.217×10-5
Rail mass per unit length	kg/m	60.64
Rail pad stiffness	N/m	6.5×107
Rail pad damping	Ns/m	7.5×104
Sleeper mass (half)	kg	125.5
Sleeper spacing	m	0.545
Ballast stiffness	N/m	137.75×106
Ballast damping	Ns/m	5.88×104
Ballast mass	kg	531.4
Sub-ballast stiffness	N/m	77.5×106
Sub-ballast damping	Ns/m	3.115×104

The stiffness of the sub-ballast layer at the first 1000 sleepers is given in Table 2. The stiffness is reduced at the last 800 sleepers corresponding to the distance 545 m to 981 m. The sub-ballast stiffness profile contains six levels of stiffness loss as shown in Fig. 3. The stiffness is changed linearly from one area to another one to prevent any instability in the model.

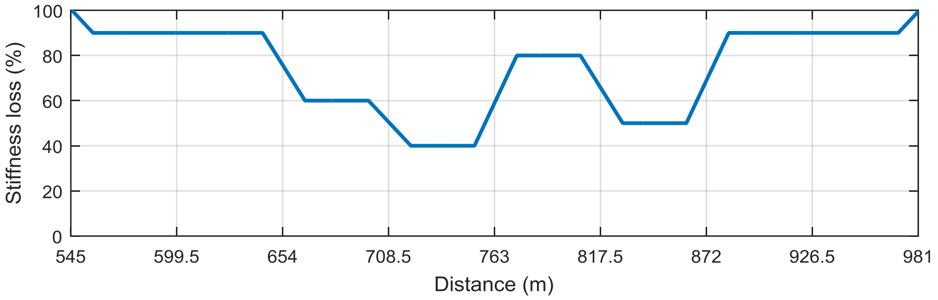

Figure 3: The track stiffness profile.

3. RESULTS

3.1. Profile deflection

The train is simulated to pass over the track at a speed of 100 km/hr. The rail deflection when the train is over the healthy area is compared to the one when the train is at a distance between 545 to 654 m, where there is a 10% loss of stiffness in the sub-ballast. The rail has maximum negative deflections at four wheel locations. The rail is more deflected at the locations of the first and third wheels when the stiffness is reduced. The deflections at the second and fourth wheels are almost unchanged. As the rail deflection is changed under the first wheel, the slope of the deflection is also changed at this area. As the train moves forward, the rail vertical velocity at any point defines the slope of the rail deflection at that point. Therefore, it is possible to detect the track stiffness change by monitoring the velocity of the rail around the first wheel.

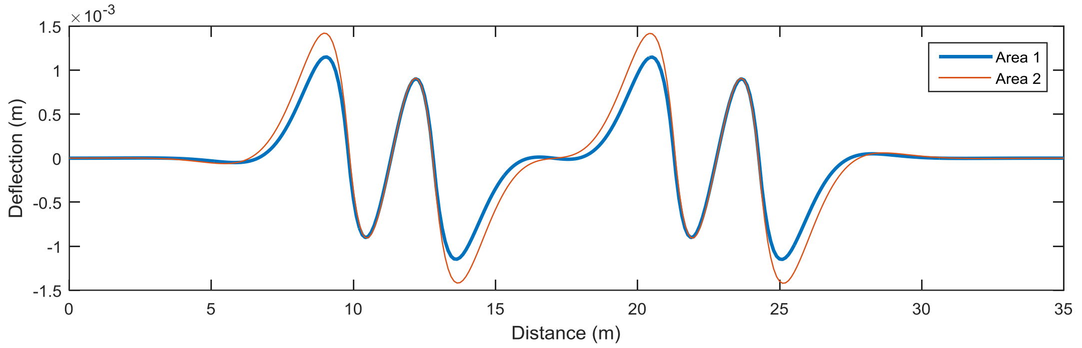

Figure 4: Rail deflections for two levels of sub-ballast stiffness.

3.2. Instantaneous measurements

The accelerations of the first and second axles are measured (Fig. 5) when the train passes over the damaged track. It is shown that the change in the track stiffness creates some changes in the amplitude of the acceleration of the second axle, but there are small changes in the first axle response. It shows that the axle acceleration response hardly provides useful information about the track stiffness.

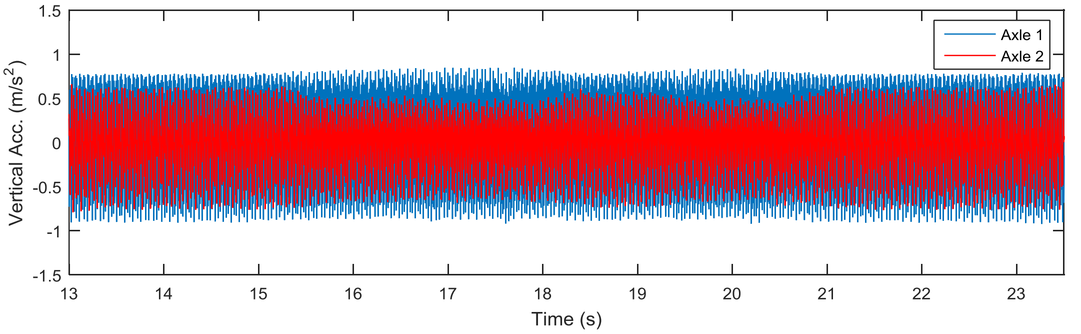

Figure 5: Acceleration responses measured at the axles.

It is proposed in this paper to measure the instantaneous velocity of the rail at four points. Points 1 and 2 are located at 0.6 m and 1.2 m in right of the first wheel, point 3 is under the first wheel and point 4 is at 0.6 m in the left of the first wheel, under the train at moving coordinates. The velocity of the rail at each point represents the slope of the rail deflection at that point. It can be seen that the slopes of the deflections at points 1, 2 and 3 are positive and at point 4 is negative. As it is expected from Fig. 3, the slopes under the wheel are very small and close to zero. The slopes at point 4 are slightly changed when the track stiffness is changed. Therefore, the measurements at points 1 and 2 provide more useful information about the track stiffness. There are clear changes at the slopes of the deflections at these points due to the changes in the track stiffness.

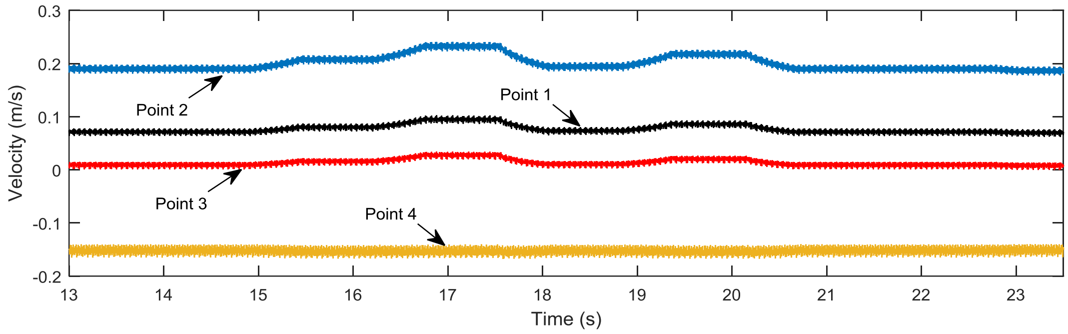

Figure 6: Velocity responses measured under the first axle.

The instantaneous velocity measurements include high frequency oscillations due to the dynamic vibrations of the track. A moving average filtering, which averages the data over 200 points, is applied to the instantaneous velocity measurements. It can be seen that the filtered responses (Fig. 7) provide more clear information about the track stiffness change.

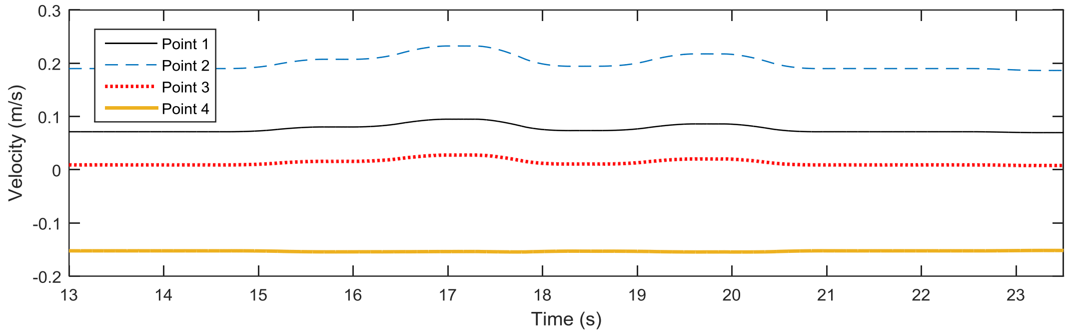

Figure 7: Filtered velocity responses measured under the first axle.

4. CONCLUSIONS

This paper studies the application of instantaneous velocity measured on a moving train for detecting railway track stiffness changes. A train carriage equipped with laser vibrometers is employed. The rail velocity responses at four points under the first axle of the train are measured. It is shown that these responses provide the slopes of the rail deflections. It is concluded that track stiffness changes can be detected by monitoring the velocity measurements.

5. ACKNOWLEDGMENTS

The authors wish to express their gratitude for the financial support received from Science Foundation Ireland towards this investigation under the US-Ireland Partnership Scheme

6. REFERENCES

Bocciolone, M., Caprioli, A., Cigada, A. & Collina, A. (2007). "A measurement system for quick rail inspection and effective track maintenance strategy". *Mechanical Systems and Signal Processing,* 21(3)**,** 1242-1254.

Cantero, D. & Basu, B. (2015). "Railway infrastructure damage detection using wavelet transformed acceleration response of traversing vehicle". *Structural Control & Health Monitoring,* 22(1)**,** 62-70.

Flintsch, G. W., Ferne, B., Diefenderfer, B., Katicha, S., Bryce, J. & Nell, S. (2012). "Evaluation of Traffic-Speed Deflectometers". *Transportation Research Record,* 2304)**,** 37-46.

Lederman, G., Chen, S. H., Garrett, J., Kovacevic, J., Noh, H. Y. & Bielak, J. (2017a). "Track-monitoring from the dynamic response of an operational train". *Mechanical Systems and Signal Processing,* 87(1-16.

Lederman, G., Chen, S. H., Garrett, J. H., Kovacevic, J., Noh, H. Y. & Bielak, J. (2017b). "Track monitoring from the dynamic response of a passing train: A sparse approach". *Mechanical Systems and Signal Processing,* 90(141-153.

Malekjafarian, A., McGetrick, P. J. & OBrien, E. J. (2015). "A Review of Indirect Bridge Monitoring Using Passing Vehicles". *Shock and Vibration*.

Malekjafarian, A. & OBrien, E. J. (2017). "On the use of a passing vehicle for the estimation of bridge mode shapes". *Journal of Sound and Vibration,* DOI: 10.1016/j.jsv.2017.02.051(

Molodova, M., Li, Z. L. & Dollevoet, R. (2011). "Axle box acceleration: Measurement and simulation for detection of short track defects". *Wear,* 271(1-2)**,** 349-356.

OBrien, E. J., Bowe, C. & Quirke, P. Determination of vertical alignment of track using accelerometer readings. IMechE Stephenson Conference for Railways: Research for Railways, 21-23 April, 2015, 2015.

Real, J., Salvador, P., Montalban, L. & Bueno, M. (2011). "Determination of rail vertical profile through inertial methods". *Proceedings of the Institution of Mechanical Engineers Part F-Journal of Rail and Rapid Transit,* 225(F1)**,** 14-23.