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Alexander Remennikov
University of Wollongong, alexrem@uow.edu.au

Sakdirat Kaewunruen
University of Wollongong, sakdirat@hotmail.com

http://ro.uow.edu.au/engpapers/284

Publication Details

This paper was originally published as Remennikov, A & Kaewunruen, S, Investigation of vibration characteristics of prestressed concrete sleepers in free-free and in-situ conditions, Australian Structural Engineering Conference 2005 (ASEC 2005), Newcastle, Australia, 11-14 September, 2005 [CD ROM]. Copyright Institution of Engineers Australia.

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Investigation of Vibration Characteristics of Prestressed Concrete Sleepers in Free-Free and In-situ Conditions

A. Remennikov and **S. Kaewunruen**
University of Wollongong, Wollongong, NSW, Australia

1. Introduction

The Australian railway industry paid approximately 25–35 percent of its 1998 annual budget on rail track maintenance. The replacement costs of rails and sleepers were a considerable part of the expense (Yun & Ferriera, 2003). Ballasted railway track has become very common in rolling stock transportation and freight, especially in Australian coal and mining businesses. Two major parts of ballasted track are the super-structure and the sub-structure. The super-structure is made up of steel rails, the fastening systems and sleepers; whilst the ballast, sub-ballast, sub-grade and formation, form the sub-structure. Figure 1 illustrates the ballasted track components. Esveld (2001) notes that ballasted track has many advantages; for example, the construction costs are comparatively low, the maintenance and repair of track and its components are convenient, it has high damping and very good drainage properties, and noise can be controlled. Since railway track is always subjected to a variety of time-dependent loads, understanding the dynamic track behaviour is essential in order to evaluate the structural safety and service life of the railway track components.

Traditionally, sleepers are the track components resting on the ballast formation transversely as shown in Figure 1. Railway sleepers were first made in timber, and then a limited number of steel sleepers were used, followed by the now popular concrete sleepers. The majority of modern railway sleepers used in Australia are the prestressed concrete sleepers. In general, the sleepers are required to:

- support and restrain the rail foot;
- sustain and distribute loads from the rail foot to the underlying ballast;
- maintain the rail gauge and shape, and preclude rail inclination and track instability;
- withstand longitudinal, lateral and vertical rail movements;
- provide insulation between parallel rails, and
- resist wearing and loading, and endure extreme weather conditions from cold to hot, and from rain to drought.

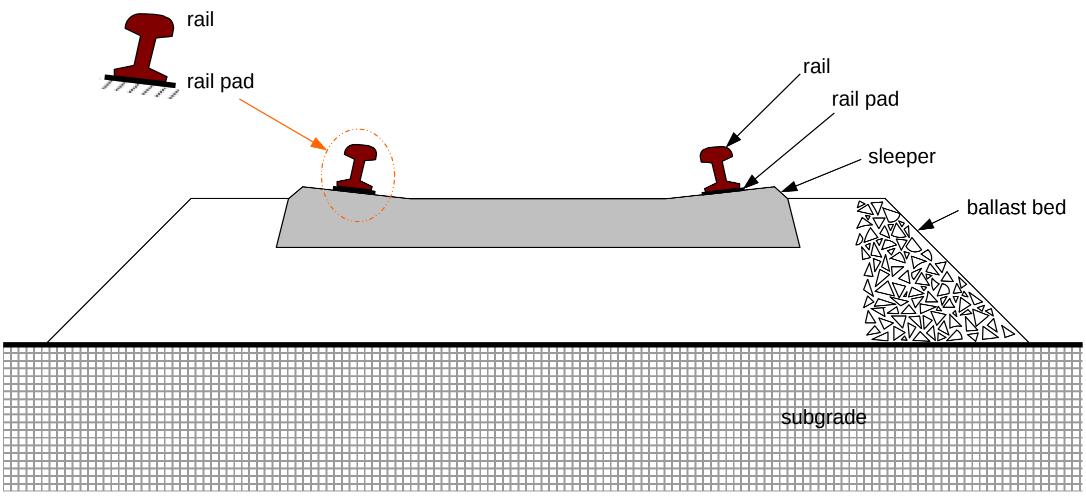
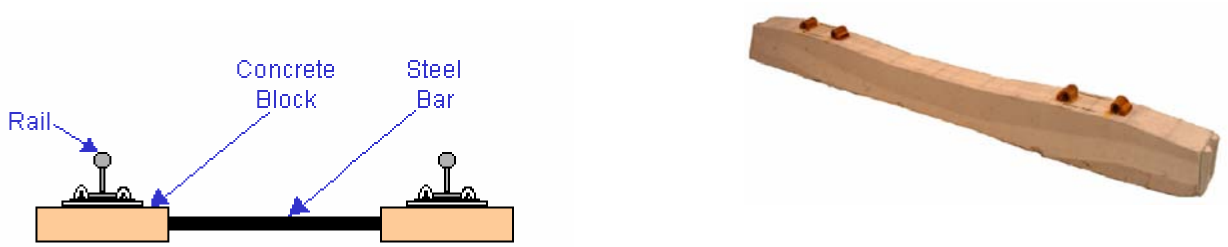


Figure 1 Typical ballasted track structure

There are two commercially available types of concrete sleepers: twin-block and monoblock sleepers, as shown in Figure 2. The former sleepers were originally developed in France and used in Europe, India, Brazil, and Mexico. The later ones first came from the UK and have been adopted in countries such as Australia, Canada, China, Japan, the UK, the USA, and the former USSR (FIP, 1987). Due to the nature of dynamic loadings on railway track, the vibration characteristics of concrete sleepers are essential in analysis and design procedures. Also, to develop and validate a numerical simulation of rail track, the free vibration characteristics of the sleepers in various conditions are needed. Archives of vibration response measurements and parameters of sleepers can help engineers to identify the vibration-based damage or remotely monitor the sleeper health, since it is clear that the sleeper damage occurs mostly at resonant frequencies of the sleepers (Grassie, 1995). The resonant vibrations of sleepers affect not only the sleepers themselves, but also the wheel–rail interaction forces. These effects have been analytically studied by Clark et al. (1982), Grassie and Cox (1985), and Knothe and Grassie (1993). Due to their wide use, the design and maintenance of prestressed concrete sleepers is a major concern to Australian track engineers.

There have been a number of studies related to the determination of dynamic properties of concrete sleepers. Modal analysis is one of the widely used techniques to examine the vibration characteristics of concrete sleepers. Ford (1988) performed modal analysis on a concrete sleeper in free-free condition using an electrodynamic shaker. Dahlberg and Nielsen (1991) developed an analytical model for analysing dynamic behaviour of concrete sleepers in both free-free and in-situ conditions. Based on the experimental results, a two-dimensional dynamic modelling for vibration analysis of concrete sleepers was done by Grassie (1995). It was found that the Timoshenko beam element was the best approximation of the concrete sleepers, even though the elastic properties of prestressed concrete sleepers may not be precise. Recently, Gustavson (2000) and Vincent (2001) performed the three-dimensional finite element modelling and modal testing of concrete sleepers in free-free condition. The results were in good agreement between numerical and experimental data. In reality, however, the sleepers are placed on ballast/subgrade formation. A comprehensive sleeper-ballast dynamic interaction has rarely been studied.



a) Twin-Block b) Monoblock

Figure 2 Concrete sleepers

This paper presents results of an experimental modal analysis of prestressed concrete sleepers in both free-free and in-situ conditions. Four types of prestressed concrete sleepers were provided by the Australian manufacturers. The concrete sleepers were tested using an impact hammer excitation technique over the frequency range of interest: 0 to1600 Hz. Frequency response functions (FRFs) were measured using the Bruel&Kjaer PULSE dynamic analyser. The FRFs were processed using the STARModal analysis package to identify natural frequencies and the corresponding mode shapes for the sleepers. The conclusions are presented on the effect of boundary conditions on the dynamic properties of prestressed concrete sleepers and their use for predicting railway track dynamic responses. Vibration parameters of concrete sleepers are required for the development of a realistic dynamic model of railway track capable of predicting its responses to impact loads due to wheel burns, irregularities of the rail, so on.

2. Analytical Modal Analysis

Measurements of vibration responses in structures result in the modal parameter identification to obtain the dynamic characteristics of the structures. There are a number of methods to extract the dynamic characteristics, depending on the format of data obtained (Ewins, 1995; He & Fu, 2001).

In a dynamic system, the equation of motion of the system can usually be represented by

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{f\} \tag{1}$$

where $[M]$ is the mass matrix, $[C]$ is the damping matrix, and $[K]$ is the stiffness matrix. The harmonic force applied to the system with magnitude F and loading frequency ω is given by

$$\{f\}=F\sin\omega t=Fe^{j\omega t} \tag{2}$$

As known, a non-trivial solution to Equation (1) is $\{x\}=\{X\}e^{j\omega t}$. Substituting this solution to Equation (1) and manipulating it with Equation (2), the equation of motion becomes

$$\left(-\omega^2[M]+j\omega[C]+[K]\right)\{X\}=\{F\} \tag{3}$$

With some manipulations, transforming Equation (3) using modal coordinates by using $\{X\}=[\Phi]\{Q\}$ and the orthogonality principle, and it then yields

$$Q_i=\frac{\{\phi_i^T\}}{\omega_i^2-\omega^2+2\xi_i\omega_i\omega j}\{F\} \tag{4}$$

Recalling $\{X\}=[\Phi]\{Q\}=Q_1\phi_1+...+Q_n\phi_n$, Equation (4) can be re-written as

$$\{X\}=\left(\sum_{i=1}^{n}\frac{\phi_i\phi_i^T}{\omega_i^2-\omega^2+2\xi_i\omega_i\omega j}\right)\{F\} \tag{5}$$

Then, the receptance of the system can be identified by

$$H_{ij}(\omega)=\frac{X_i(\omega)}{F_i(\omega)}=\sum_{i=1}^{n}\frac{\phi_i\phi_i^T}{\omega_i^2-\omega^2+2\xi_i\omega_i\omega j} \tag{6}$$

Herein, ω_i denotes the resonant frequency, ϕ_i is the mass-normalized mode shape, and ξ_i represents the modal damping ratio.

Note that for viscous damping (with critical damping c_r), $\xi_i=\frac{c_i}{c_r}$; for proportional damping ($[C]=a[M]+b[K]$), $\xi_i=\frac{a}{2\omega_i}+\frac{b\omega_i}{2}$; and for hysteretic damping (η_i), $\xi_i=\frac{\eta_i}{2}$.

3. Experimental Overview

All test specimens were prestressed concrete sleepers designed in accordance with AS1085.14-2003. The dimensions and masses of the test sleepers are tabulated in Table 1. Sleepers No. 1 and 2 are the heavy- and medium-duty sleepers provided by ROCLA. Sleepers No.3 and 4 are the broad- and narrow-gauge sleepers provided by AUSTRAK. The excitation points were located on the top surface of the sleeper at every 150 mm along the perimeter. It should be noted that the number of these positions should be sufficient to represent the vibration modes of interest. In this case, an accelerometer had a fixed position whilst an instrumented impact hammer was roved along the excitation points. Figure 3 shows the experimental setup of a sleeper in free-free condition. The sleepers were suspended by very soft springs to simulate free-free boundary conditions. After performing the modal testing, the sleepers were then placed on the ballast bed that imitated the actual track construction, as illustrated in Figure 4.

Table 1 Dimensions and masses of the test sleepers

Sleeper No.	Mass (kg)	Total length (m)	At railseat (m)		At centre (m)	
			width	depth	width	depth
1	206.0	2.50	0.20	0.23	0.21	0.18
2	198.1	2.47	0.22	0.18	0.21	0.17
3	299.5	2.85	0.22	0.21	0.22	0.18
4	283.0	2.15	0.18	0.25	0.16	0.24

Figure 3 Free-free condition

Figure 4 Ballast condition

From experience, the best position for mounting the accelerometer is at the end of the sleeper. The instruments used in this study were a PCB accelerometer, the PCB impact hammer, and the Bruel&Kjaer PULSE vibration analyser. The accelerometer was mounted at the sleeper end. Using the hammer to excite vibrations in the sleeper over the frequency range 0 to1600 Hz, the 10-time average vibration responses represented by the FRFs were obtained using the PULSE system. Then, processing the recorded FRFs by STARModal gave the natural frequencies and modal damping constants of the sleeper. All procedures were performed twice per a sleeper for free-free and ballasted-support conditions.

4. Results

The results of vibration tests for Sleepers No. 1–4 are depicted in Tables 2–5. In these tables, the first five modes of vibration are presented. For all sleepers, it was found that the first bending mode in a vertical plane clearly dominated the first resonant mode of vibration both in free-free and ballast conditions. Table 2 shows the experimental dynamic properties of Sleeper No. 1 (ROCLA Heavy Duty). For a free-free condition, the lowest frequency corresponded to the fundamental bending mode, the second frequency to the second bending mode, the third frequency to the lowest torsional mode, the fourth frequency to the third bending mode, and the fifth mode to the second torsional mode. Similar modes of vibration were identified for the sleeper in the in-situ boundary condition. Of all five modes, the most significant change in natural frequencies between the free-free and in-situ conditions was the first bending mode. The maximum frequency increase was about 15 percent. However, it was found that at higher resonant frequencies, the effect of boundary conditions was remarkably decreased to only two percent difference in the forth and fifth vibration modes. Also, it should be noted that the ballast support played a significant role in increasing the damping values of all vibration modes. The maximum damping increase due to sleeper-ballast interaction was more than 50-fold in the first bending mode and the average change in other modes was between five and 10-fold. The mode shapes of ballasted sleepers were quite difficult to identify since some mode shapes were sometimes too closely spaced between each mode of vibration. The effect of boundary conditions on vibration properties of sleepers is depicted in Figure 5.

The experimental modal results for Sleeper No. 2 (ROCLA Medium Duty) are presented in Table 3. The frequency change between the free-free and in-situ conditions ranged from approximately one to 12 percent. The ballast support augmented the damping values of all vibration modes, varying from four to 35 times. Table 4 gives the results of the experimental modal analysis of Sleeper No. 3 (AUSTRAK Broad Gauge). Up to a 34 percent frequency increase was found in the lowest mode which was considerably reduced to just a few percent in the higher frequency modes. At all frequencies, with one exception, the damping ratios on the ballast condition increased in the range from six up to 25 times. The one exception was the maximum increase in the first torsional frequency. Table 5 presents the modal properties of Sleeper No. 4 (AUSTRAK Narrow Gauge). The same trends in frequencies and damping constants for the sleepers in free-free and in-situ conditions was observed.

5. Conclusion

Vibration parameters of concrete sleepers are very important for the development of a realistic dynamic model of railway track capable of predicting its dynamic responses. The results of the experimental modal analysis for prestressed concrete sleepers under different boundary conditions are presented in this paper. Four types of prestressed concrete sleepers manufactured in Australia were tested using an impact hammer excitation technique over the frequency range of interest: from 0 to 1600 Hz. It was found that the resonant frequencies and damping ratios associated with the lower mode of vibration of prestressed concrete sleepers were considerably affected by the support boundary conditions. However, the influence of the ballast condition was reduced in the higher frequency range. The dominant effect of the in-situ support was placed on the modal damping in the ballast-sleeper interaction. In addition, the mode shapes, which can indicate the deteriorated state of concrete sleepers, were affected by the ballast condition. In summary, the in-situ boundary condition had a remarkable influence on the natural frequency, modal damping, and vibration mode shape of prestressed concrete sleepers, especially in the low frequency range. It is recommended that the determined parameters of concrete sleepers be used in modelling of railways tracks where the effect of the boundary condition will be taken into account.

Table 2 Modal parameters of sleeper no.1 – ROCLA Heavy Duty

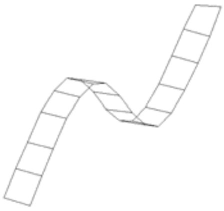
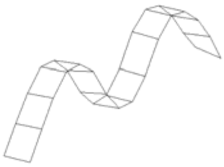
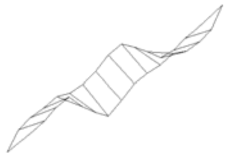
Mode	Free-Free Condition		Ballast Support	
	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
1	 135.71 (1st bending)	0.266	 155.22 (1st bending)	15.92
2	 404.83 (2nd bending)	0.298	 413.70 (2nd bending)	3.09
3	 481.36 (1st twisting)	0.331	 503.85 (1st twisting)	5.58
4	 767.84 (3rd bending)	0.279	 775.67 (3rd bending)	1.74
5	 1,155.31 (2nd twisting)	0.292	 1,168.48 (2nd twisting)	1.03

Table 3 Modal parameters of sleeper no.2 - ROCLA Medium Duty

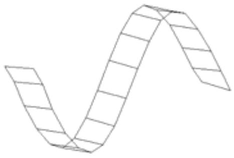
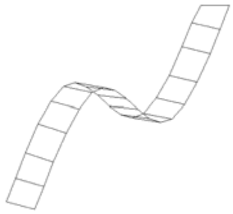
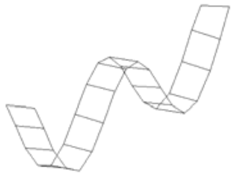
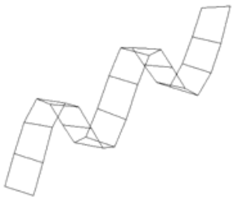
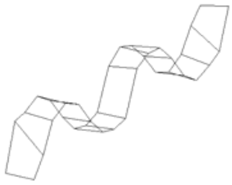
Mode	Free-Free Condition		Ballast Support	
	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
1	 123.47 (1st bending)	0.236	 138.13 (1st bending)	8.88
2	 340.49 (2nd bending)	0.333	 361.08 (2nd bending)	4.44
3	 497.70 (1st twisting)	0.308	 512.47 (1st twisting)	5.42
4	 651.50 (3rd bending)	0.297	 661.72 (3rd bending)	2.40
5	 1,026.15 (4th bending)	0.334	 1,035.98 (4th bending)	1.63

Table 4 Modal parameters of sleeper no.3 - AUSTRAK Broad Gauge

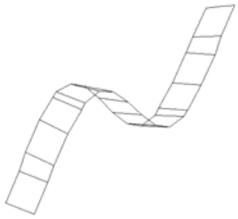
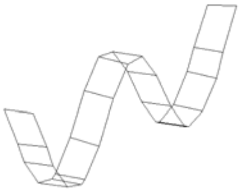
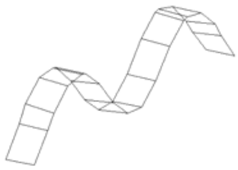
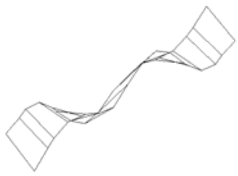
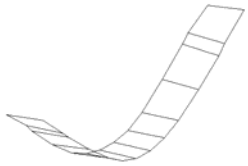
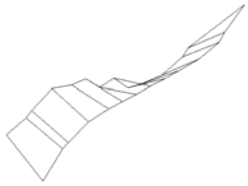
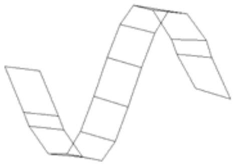
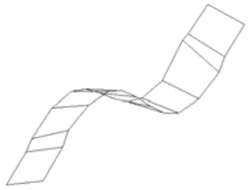
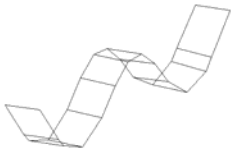
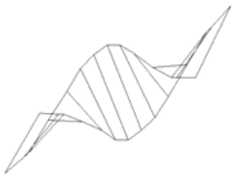
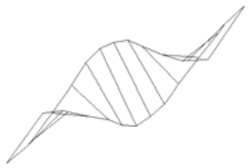
Mode	Free-Free Condition		Ballast Support	
	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
1	 112.64 (1st bending)	0.192	 150.21 (1st bending)	5.16
2	 312.50 (2nd bending)	0.269	 334.13 (2nd bending)	5.05
3	 436.60 (1st twisting)	0.274	 449.05 (1st twisting)	8.05
4	 605.51 (3rd bending)	0.239	 617.98 (3rd bending)	3.20
5	 943.53 (2nd twisting)	0.220	 963.88 (2nd twisting)	1.77

Table 5 Modal parameters of sleeper no.4 - AUSTRAK Narrow Gauge

Mode	Free-Free Condition		Ballast Support	
	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
1	 223.09 (1st bending)	0.216	 244.59 (1st bending)	8.36
2	 561.62 (1st twisting)	0.173	 565.70 (1st twisting)	4.08
3	 593.19 (2nd bending)	0.209	 603.00 (2nd bending)	2.60
4	 1,092.68 (3rd bending)	0.236	 1,100.38 (3rd bending)	1.08
5	 1,266.67 (2nd twisting)	0.242	 1,275.00 (2nd twisting)	1.75

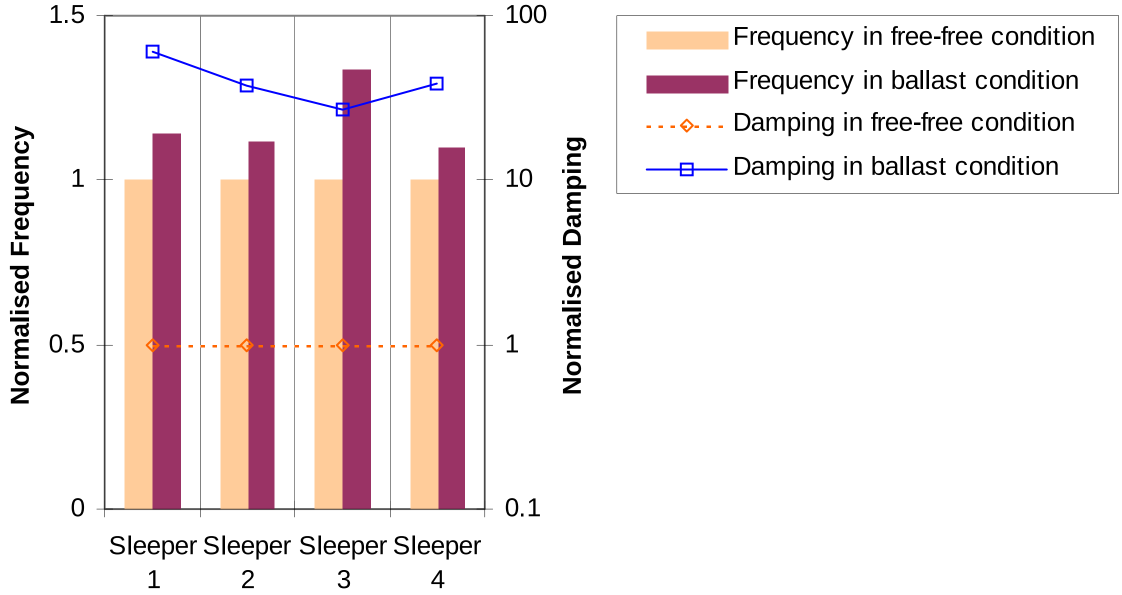


Figure 5 Effect of boundary conditions on fundamental vibration properties of sleepers

6. Acknowledgement

The authors would like to acknowledge the CRC for Railway Engineering and Technologies for the financial support as part of Project #5/23. The sleepers were provided by ROCLA and AUSTRAK. Thanks also go to technical officers, A Grant, B Ian, and I Bridge for their technical support. Also, the second author is grateful to Rail CRC for providing him the PhD scholarship throughout the period of study.

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