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DETERMINATION OF DYNAMIC PROPERTIES OF RAIL PADS USING AN INSTRUMENTED HAMMER IMPACT TECHNIQUE

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Abstract. The repeated impact of train wheels over sleepers can reduce the lifetime of a sleeper and degrade ballast. In more extreme cases it can lead to the breakdown of the concrete sleeper. Concrete sleepers are rigid compared to steel and wooden sleepers and therefore it is necessary to provide impact attenuation to prevent premature breakdown of the concrete. One of the measures employed to attenuate the effect of the impact loads on concrete sleepers has been the use of the resilient rail seat pads. Numerous analytical and numerical models have been formulated to investigate the dynamic behaviour of railway track substructures. All models require careful selection of the track component properties to satisfactorily represent track vibration response. However, there is currently no standard method available that can be used to evaluate the dynamic properties of the rail pads. At the University of Wollongong, an instrumented hammer was used to excite an equivalent single degree-of-freedom system (SDOF), incorporating a rail pad as a resilient element, to determine the dynamic properties using methods of modal analysis. The analytical SDOF dynamic model was applied to best fit the experimental modal measurements that were performed in a frequency range of 0–500 Hz. The curve fitting gives such dynamic parameters as the effective mass, dynamic stiffness, and dynamic damping constant, all of which are required for numerical modelling of a railway track.

INTRODUCTION

Railways have played an important role in spreading population over large areas of Australia. The traditional ballasted track system, consisting of rail tracks, pads, and sleepers laid on ballast and subgrade, is used throughout this country. In this system, rail pads, usually made from polymeric compound materials, are mounted on rail seats and tend to attenuate the dynamic stress from axle loads and wheel impact from both regular and irregular train movements. These pads are crucial as they act as a softening medium between rail track and sleepers. Previous problems arising from improper or inadequate utilization of pads include cracking of sleepers at rail seats, high settlements of global and local tracks, and ballast/subgrade breakage from heavy tamping. These problems result in lower load capacity and deficient structural adequacy of track substructures, requiring a costly maintenance and rehabilitation budget. Thus, in addition to minimizing unpredictable maintenance and repairs, rail pads have been of interest to rail engineers as they reduce the dynamic stresses and impact loads on sleepers.

To gain a better insight into the dynamic characteristics of rail pads, it is important to carry out laboratory tests on their dynamic properties. These are also used in the numerical simulation of track dynamics. The numerical solution confirms the reliability and integrity of the railway substructures. It comes after the determination of dynamic properties of each track component, i.e. concrete sleepers, rail pads, and the ballast support. At present, there are many types of rail pads, such as high density polyethylene (HDPE) pads, resilient rubber pads, and resilient elastomer pads, all of which have different surface profiles. Examples of plain and studded profiles are illustrated in Figure 1. Until recently, the investigation of the dynamic characteristics of resilient pads had been limited, even though resilient rail pads are used extensively on all major Australian railway networks. The dynamics of the resilient type have been studied mostly based on a two-degree-of-freedom (2DOF) model [1–4]. In this paper, a SDOF-based method was developed to help railway track engineers to evaluate the realistic values of the dynamic properties of rail pads required for the design and maintenance of railway tracks. Figure 2 displays typical ballasted track construction and a typical railway track model used for numerical simulations. Figure 3 demonstrates a test setup of a SDOF system. An analytical solution was used to best fit the vibration responses. Vibration response recordings were obtained by impacting the rail with an instrumented hammer. Bovey [5] was one of the first researchers to use an impact method to determine the dynamic characteristics of railway installations. In this paper, the curve fitting method was applied to the frequency response functions (FRFs) obtained from modal testing measurements to extract the effective mass, dynamic stiffness and damping of resilient-type rail pads.

THEORETICAL REVIEW

Rail pads can be arranged as the elastic and dashpot components of a simple mass-spring-damper SDOF system by placing the pads between a steel rail and a rigid block, as shown in Figure 3. The dynamic characteristics of rail pads in the vertical direction can be described by the well-known equation of motion:

$$m\ddot{x} + c_p\dot{x} + k_p x = f(t) \qquad (1)$$

$$\omega_n^2 = {}^{k_p}\!/_{m}, \; 2\zeta\omega_n = {}^{c_p}\!/_{m}, \text{ or } \zeta = {}^{c_p}\!/_{2\sqrt{k_p m}} \qquad (2a,\ b,\ c)$$

where m, c, and k generally represent the effective rail mass, damping and stiffness of a rail pad, respectively. Taking the Fourier transformation of (1), the frequency response function can be determined. The magnitude of FRF is given by

$$H(\omega) = \frac{\frac{1}{m}}{\sqrt{\left(\omega_n^2 - \omega^2\right)^2 + \left(2\zeta\omega\omega_n\right)^2}} \qquad (3)$$

Substituting equations (2) into equation (3) and using $\omega=2\pi f$, the magnitude of the frequency response function H(*f*) can be represented as follows:

$$H(f)=\frac{1}{m}\frac{4\pi^2\left(\frac{m}{k}\right)f^2}{\sqrt{\left[1-4\pi^2\left(\frac{m}{k}\right)f^2\right]^2+\left[4\pi^2\left(\frac{m}{k}\right)\left(\frac{c^2}{km}\right)f^2\right]^2}} \tag{4}$$

This expression contains the system parameters *m*, *k* and *c* that will later be used as the curve-fitting parameters.

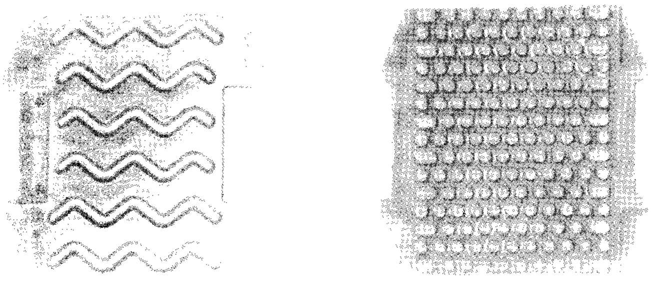
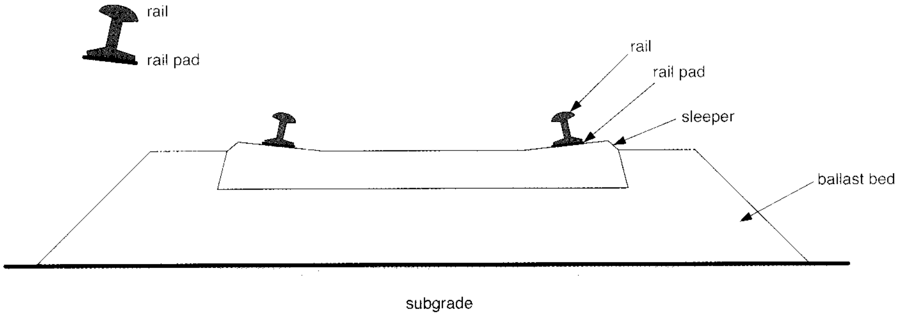

(a) Plane surface (b) Studded surface

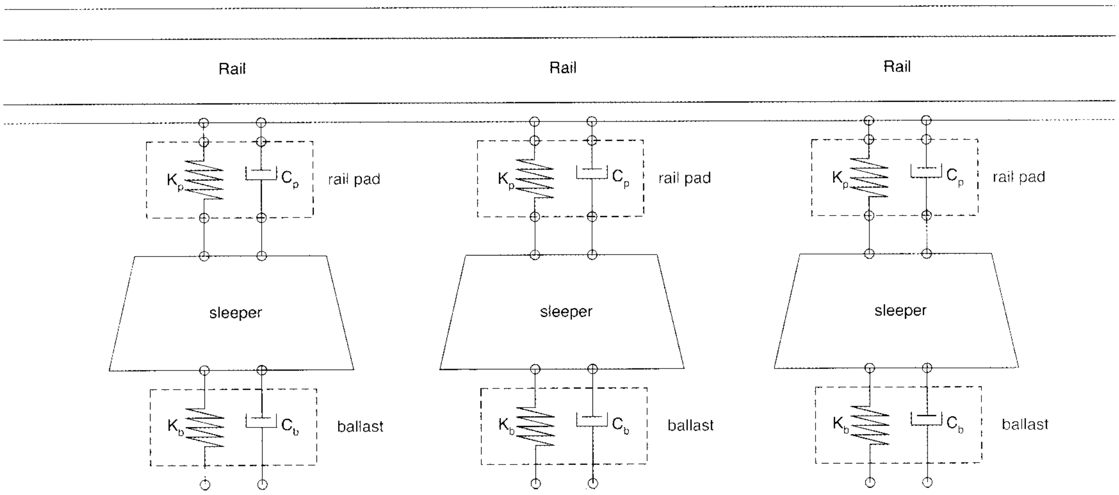
Figure 1 Examples of rail pad profiles

VIBRATION RESPONSE MEASUREMENTS

To measure the vibration response of the rail pads, an accelerometer was attached to the top surface of the railhead, as illustrated in Figure 3. The mass of the rail segment was 21.25kg, and the mass of the e-Clip fastening system was 0.75kg. It should be noted that a test rig was rigidly mounted on a "strong" floor (1.5m deep of heavily reinforced concrete), the fundamental frequency of which was significantly higher than the frequency range of interest for the rail pads. The railhead was impacted vertically with an instrumented hammer and the measurements were taken within a frequency range of 0–500 Hz. The FRF was then measured by the Bruel&Kjaer PULSE modal testing system, which was connected to a computer. Measurement records also included the impact forcing function and the coherence function. It is known that the FRFs describe the modal parameters of the vibrating rail system. The coherence function represents the quality of FRF measurements and should be close to unity. As an example, the properties of the PANDROL resilient rubber pad (studded type, 6.5 mm thick) were determined using the test rig and the results are presented in Figure 4. They included: the transient impact forcing function (Figure 4a); the vibration responses to the impact (Figure 4b); the magnitude FRF (Figure 4c) derived

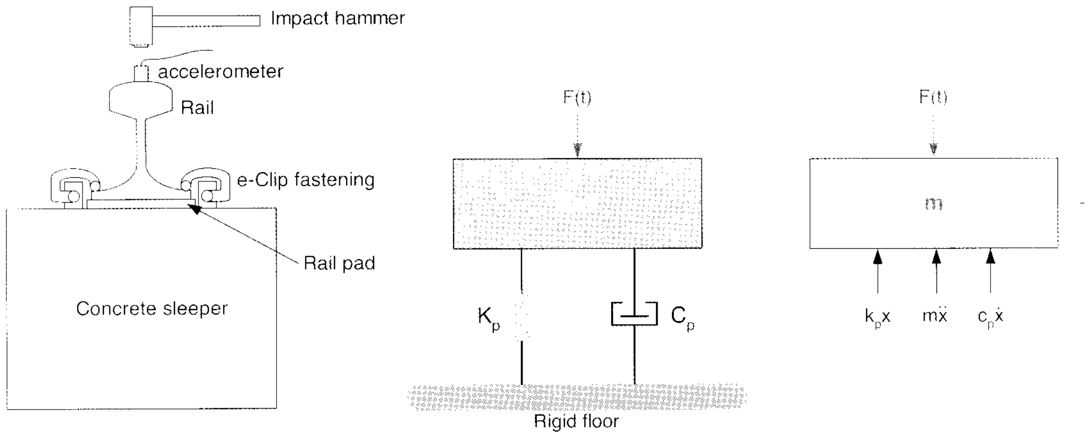


a) Typical ballasted track system



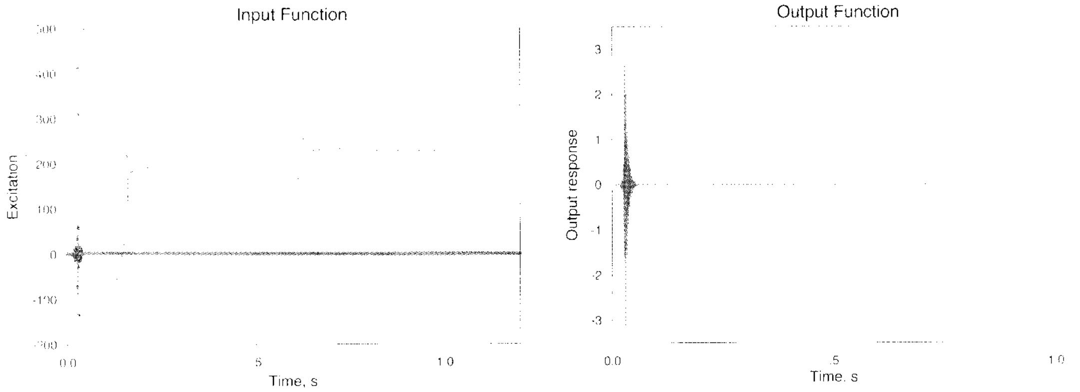
b) Numerical model of track system and dynamic properties of track components

Figure 2 Track Simulation

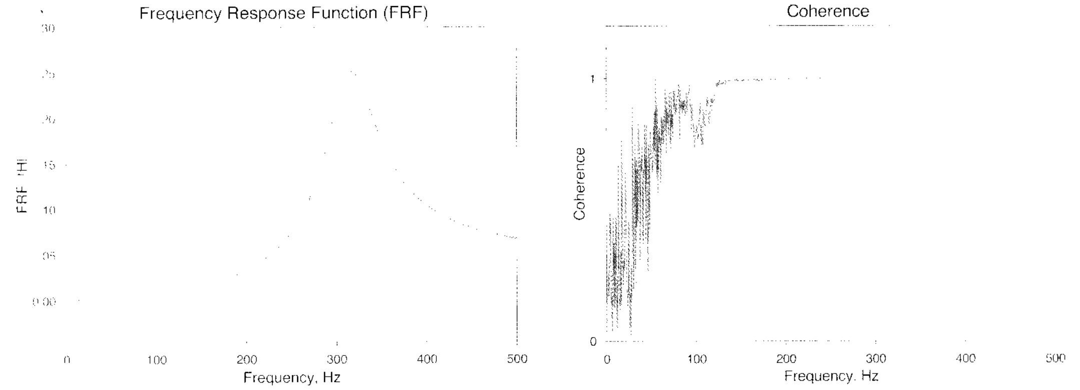


a) Schematic Test Rig b) Analytical Model c) Free Body Diagram

Figure 3 Experimental rig for testing rail pads



a) transient forcing function b) transient dynamic response



c) FRF d) coherence function

Figure 4 Vibration response measurements using impact instrumented hammer

from the vibration responses and the forcing functions logged; and the coherence function (Figure 4d) that confirmed a high degree of linearity between input and output signals.

BEST FITTING FRF

Parts of FRFs, in particular in the vicinity of the resonant frequencies, supplied detailed information on the properties of the tested component. The extraction of these dynamic properties was achieved using a curve-fitting approach. In this approach, the FRF of the model (4) was tuned to be as close as possible to the recorded FRF in a frequency band around the resonant frequency. Curve-fitting routines can be found in many general mathematical computer packages (e.g. MATLAB, Mathematica, Maple), or using specialized curve-fitting computer codes (e.g. DataFit). Figure 5 demonstrates the curve fitting performed by DataFit and gives the system

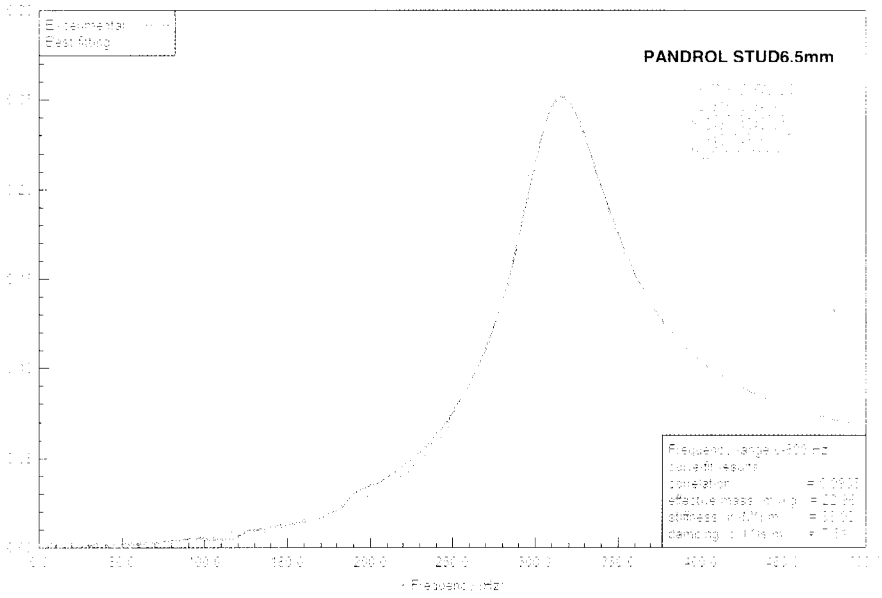


Figure 5 FRF Best Curve Fitting

Table 1 Dynamic properties of new rail pads tested at UoW

Test place	Material	Shape	Area (cm^2)	Thickn. (mm)	Preload (kN)	Temp. (Celsius)	Nr	Dynamic stiffness (MN/m)	Damping constant (kNs/m)
UOW	HDPE	Full material	208	7.5	20	20	3	470	6
	HDPE	Full material	246	10.0	20	20	3	628	4
	Rubber	Studded, double side	225	6.5	20	20	3	89	8
	Rubber	Studded, double side	267	10.0	20	20	3	66	5

parameters that are comparable to the parameters found in the open literature [6, 7] using impact-load testing. The results in Figure 5 show an excellent agreement between the analytical solution and the experimental data, since the correlation coefficient r^2 is equal to 0.9988, or less than 0.12% error. The dynamic properties of HDPE and rubber pads are also tabulated in Table 1. The results in Table 1 are in close agreement with the previous research results [6] given in Table 2. These data were developed by the Track Testing Center (TTC) of Spoomet, South Africa, and by TU Delft (DUT) of the Netherlands.

CONCLUSIONS

An alternative strategy based on the SDOF vibration response measurement for determining the dynamic properties of rail pads was proposed. The strategy was demonstrated to be simple and reliable, and was shown to be a fast and non-destructive test method to assess the dynamic stiffness and damping constant of all kinds of rail pad types available in Australia. The approach enables testing of new types of rail pads as well as evaluation of the influence of age of pads on their dynamic characteristics. The proposed impact method can be generalized to include the modal analysis of more complicated track components. Recently, field investigations were undertaken using the proposed technique on a heavy haul coal line in Central Queensland with the cooperation of Queensland Rail. It was found that the proposed technique yielded reliable and repeatable results in field tests as well as in laboratory conditions. These new results will be presented in future publications by the authors.

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Table 2 Dynamic properties of new rail pads tested at TTC and DUT [6]

Test place	Material	Shape	Area (cm²)	Thickn. (mm)	Preload (kN)	Temp. (Celsius)	Nr	Dynamic stiffness (MN/m)	Damping constant (kNs/m)
	UK Hyfref 6358	Insert, loaded withour baseplate		8.5	25		3	130	20
	RSA EP2/EP2	Base plate + insert		7.0-8.5	25		3	90	17
	RSA EP2 8358	Pad + insert		5.5+5.5	25		3	110	23
	HDPE (lab)	Full material		12.0	25			375	7
	HDPE (field)	Full material		12.0				1200	50
	Rubber	Studded		10.0	25			75	
	Corkalas (soft)	Rubber bonded cork	196	5.2	20	20	5	970	32
	Corkalas (norm)	Rubber bonded cork	196	4.7	20	20	5	1420	34
	Rubber (hard)	Full material	193	4.9	20	20	5	2990	29
	Lupolan V3510k	Full material	197	5.0	20	18	5	3030	29
	Amilial EM400	Full material	197	5.0	20	18	5	1840	14
	Amilial EM400	Full material	195	9.4	20	25	3	1210	12

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