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State dependent properties of rail pads

Sakdirat Kaewunruen
RailCorp, sakdirat@hotmail.com

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

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S Kaewunruen †
RailCorp – Track Engineering, Sydney, NSW

AM Remennikov
School of Civil, Mining and Environmental Engineering, Faculty of Engineering,
University of Wollongong, Wollongong, NSW

SUMMARY: *A rail pad is one of the main components in ballasted railway track systems. It is inserted between the rail and the sleeper to attenuate dynamic wheel/rail interaction forces, preventing the underlying railway track components from excessive stresses. Generally, the dynamic design of tracks relies on the available data, which are mostly focused on the structural condition at a specific toe load. Recent findings show that track irregularities could significantly amplify the loads on railway tracks. This phenomenon gives rise to a concern that the rail pads may experience higher deterioration rate than anticipated in the past. On this ground, an innovative test rig for estimating the dynamic properties of rail pads has been devised at the University of Wollongong. A non-destructive methodology for evaluating and monitoring the dynamic properties of the rail pads has been developed based on an instrumented hammer impact technique and an equivalent single degree-of-freedom system approximation. This investigation focuses on the state-dependent model of rail pads where the dependent effects of frequency and static load contents can be distinguished. Based on the impact-excitation responses, the analytical state-dependent 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 modern numerical modelling of a railway track.*

1 INTRODUCTION

A rail pad is an important component of railway tracks. Commonly, it is made from polymeric compound, rubber or composite materials. The rail pads are installed on rail seats in order to attenuate the dynamic content from axle loads and wheel impacts from both regular and irregular train movements. In the design and analysis of railway tracks, numerical models are often employed to aid railway civil engineers in service and failure analysis, and maintenance prediction. A variety of numerical methods have been adopted for modelling each component of railway tracks to achieve a more realistic representation of the real structures (Oscarsson, 2002; Neilsen & Oscarsson, 2004). It should be noted that the wagon burden or wheel passage and the fastening system impart the dynamic loading and the static preloading to the track, respectively. However, the current numerical models or simulations of railway tracks mostly exclude the time- and frequency-dependent effect on the non-linear dynamic behaviour of rail pads, although it is evident that deterioration rate has significant influence on the dynamic rail pad properties that affect the dynamic responses of railway tracks (Grassie & Cox, 1984; Wu & Thompson, 1999). A reason is the lack of information on the dynamic behaviour of rail pads at different ages, and the knowledge of the dynamic wheel-load distribution to rail pads and other track components. Current rail pad models consist of a spring-dashpot system as a single degree of freedom system (Remennikov et al, 2006). A recent track model shows that more accurate track responses can be obtained using a new rail pad model, so called "state-dependent model" (Neilsen & Oscarsson, 2004). The new model attaches an additional spring into the dashpot mechanism. It is found that the state-dependent properties of the rail pads have not been determined adequately. This paper discusses the model formulation that includes the state-dependent properties of the rail pads.

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† Corresponding author Dr Sakdirat Kaewunruen can be contacted at sak.kaewunruen@railcorp.nsw.gov.au.

The outcomes will help the recent railway research at the University of Wollongong (UoW) address the dynamic and impact load transfer problem in railway tracks as the frequency-dependent content can be quantified from the new rail pad model concept. This data is highly sought as an independent investigation apart from supplier's values and could be incorporated into the modern numerical modelling of a railway track, in order to determine the effects of high frequency loading in the future.

There are many different 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. Figure 1 shows the examples of HDPE and studded-profile rail pads. It should be noted that dynamic responses of the track relate directly to impact noise and wear levels of railway tracks and wheels. The common dynamic model of rail pads consists of two main values: dynamic stiffness and damping coefficient. In this paper, a new non-linear dynamic model takes care of more variables, which is so-called "state-dependent viscoelastic model" as shown in figure 2.

To obtain such properties, the dynamic testing of rail pads in laboratory or on track is required. From the dynamic response measurements, both linear and non-linear properties can be estimated by optimising the objective formulations of the desired dynamic model. The traditional spring-dashpot model has been applied to the various studies on vertical vibrations of railway tracks (Grassie & Cox, 1984; Cai, 1992; Knothe & Grassie, 1993; Oscarsson, 2002). In recent years, the state-dependent model of rail pads, where an additional spring is presented in series with the dashpot, has been proposed for use as an alternative model for rail pads (Fenander, 1998; de Man, 2002; Neilsen & Oscarsson, 2004; Maes et al, 2006; Remennikov et al, 2006).

De Man (2002) noted a benefit of the state-dependent model that the model can separate influences of loading frequency from the influences of preload, in case of harmonic or cyclic testing on frequency-dependent materials. With regards to the identification of dynamic rail pad characteristics, Grassie & Cox (1984) recommended that it be the best way to determine such dynamic parameters by extracting from operational vibration measurement or field testing by an impact hammer or dynamic exciter. However, it is important to note that the dynamic properties could only be determined at the resonant frequency, when using an impact hammer as the exciter.

A number of investigations of the dynamic characteristics of resilient pads have been found recently in literature (Grassie, 1989; Van't Zand, 1993; de Man, 2002; Remennikov & Kaewunruen, 2005; Kaewunruen and Remennikov, 2005a; 2005b; Remennikov et al, 2006; Maes et al, 2006). Interestingly, some studies have been based on a two-degree-of-freedom (2DOF) model (Fenander, 1997; 1998; Thomson et al, 1998; Knothe et al, 2003). From the literature, single-degree-of-freedom (SDOF) dynamic model has popularly been applied to the laboratory setup of a number of investigations. Instrumented hammer impact technique is of very wide use in these kind of tests due to its proven effectiveness and mobility (Kaewunruen & Remennikov, 2006; 2008).

In this paper, a SDOF-based method using the state-dependent model concept is used to evaluate

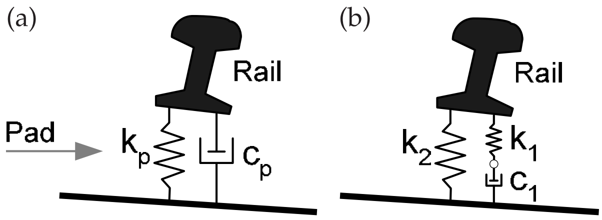

Figure 2: Rail pad models – (a) viscous damping and (b) state-dependent models.

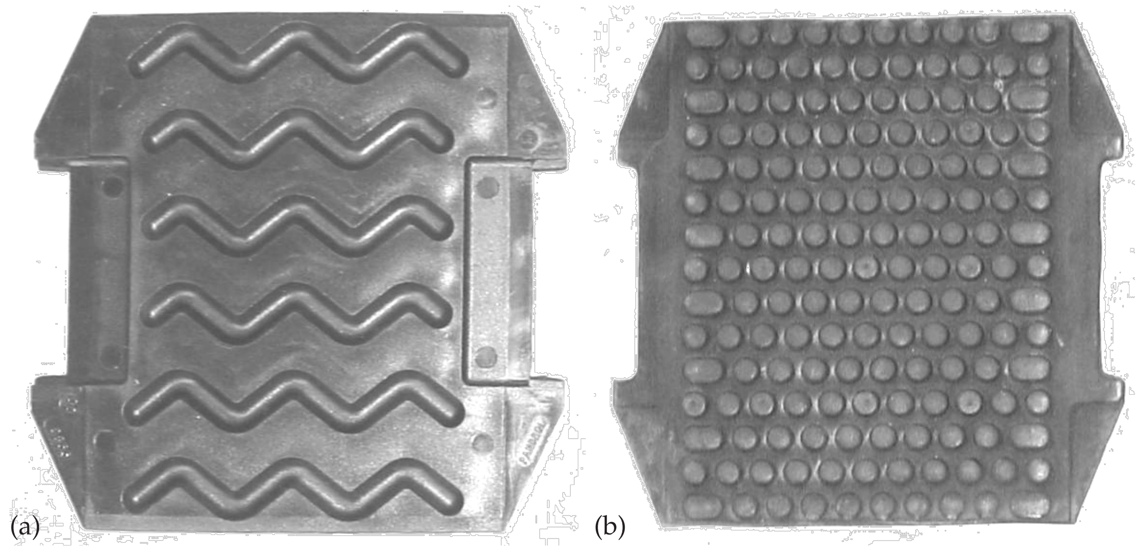

Figure 1: Rail pad specimens – (a) HDPE and (b) studded.

the dynamic properties of rail pads. Instrumented hammer impact technique is employed in order to benchmark with the field trials and previous studies (Kaewunruen & Remennikov, 2005c). Figure 3 demonstrates a typical ballasted railway track. An analytical formulation is derived to best fit the vibration responses. The effective mass, dynamic stiffness and damping of resilient-type rail pads are obtained from the least-square optimisation of the frequency response functions (FRFs) obtained from modal testing measurements.

2 THEORETICAL OVERVIEW

2.1 State dependent model

Rail pads can be simplified as the elastic and dashpot components of a mass-spring-damper SDOF system by installing the pads between a steel rail and a rigid block, as shown in figure 2(b). The dynamic characteristics of rail pads in the vertical direction can be described by the well-known equation of motion:

$$m\ddot{x} + \frac{x}{\frac{1}{k_1} + \frac{1}{\omega \cdot c_1}} + k_2 x = f(t) \tag{1}$$

where m, c_1, k_1 and k_2 generally represent the effective rail mass, damping, and frequency-dependent and frequency-independent stiffness of a rail pad, respectively. Generalised displacement x is defined by Fourier function and ω is the radial vibration frequency.

Taking the Fourier transformation of equation (1), the FRF can be determined. The magnitude of FRF is given by:

$$H(\omega) = \frac{1/m}{\sqrt{\left[\frac{k_2}{m} - \omega^2\right]^2 + \left[\frac{1}{\frac{m}{k_1} + \frac{m}{\omega \cdot c_1}}\right]^2}} \tag{2}$$

This expression contains the system parameters m, k_1, k_2 and c_1 that will later be used as the curve-fitting parameters.

It should be noted that the analytical formulation of the traditional rail pad model shown in figure 2(a) was previously derived and can be found in Remennikov & Kaewunruen (2005).

2.2 Model comparison

Table 1 shows the comparison of the mechanical model definitions of rail pads. The stiffness and damping constants are varied with the loading frequency as depicted in figure 4. It is shown that when the loading frequency increases, the dynamic stiffness tends to increase but the damping coefficient tends to decrease.

In the table:

- K_t = total stiffness (N/m)
- C_t = total viscous damping (Ns/m)

Table 1: Rail pad model comparison.

Property	Traditional model	State-dependent model
K_t	$= K_p$	$= \alpha K_1 + K_2$
C_t	$= C_p$	$= \alpha\beta C_1$

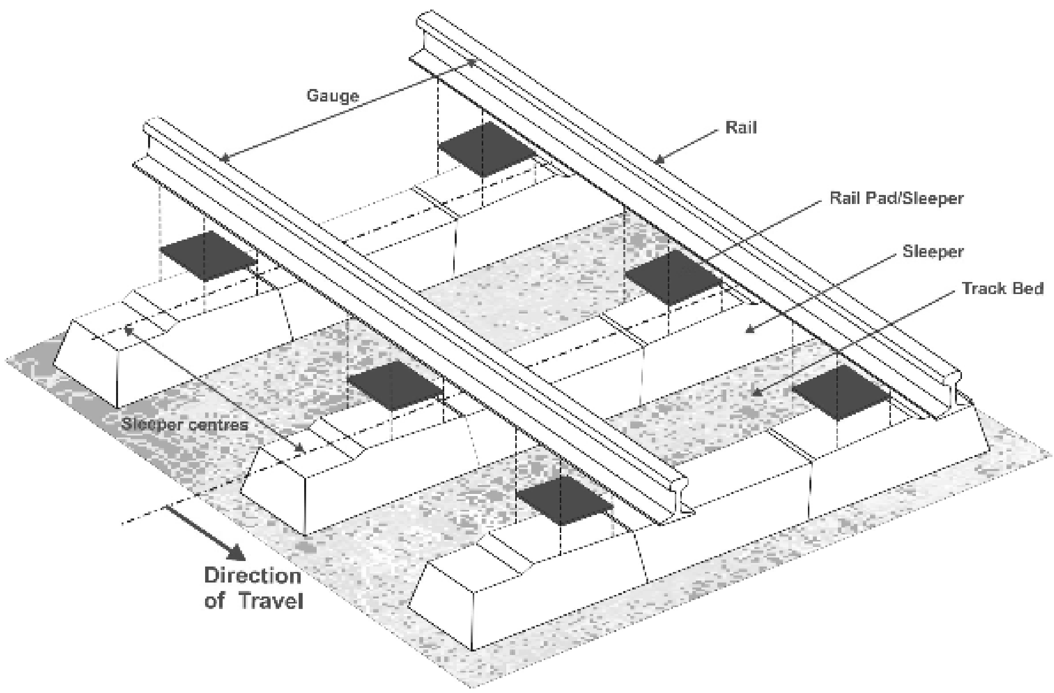

Figure 3: Typical ballasted railway track (Remennikov et al, 2008).

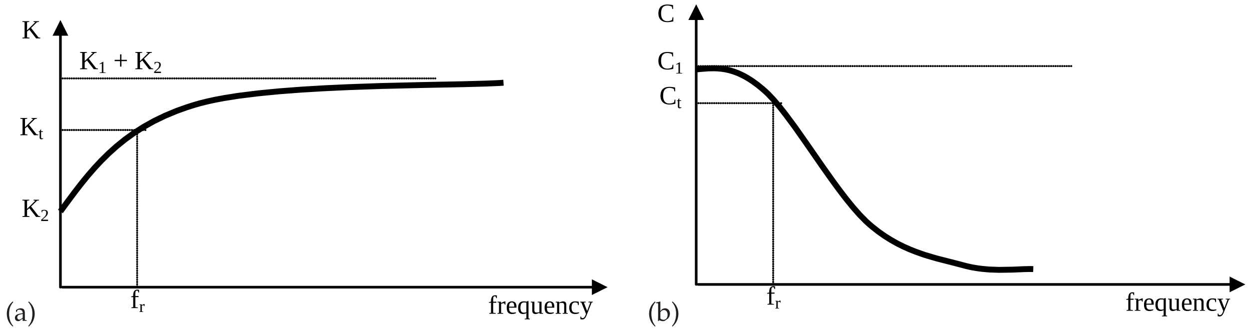

Figure 4: Frequency-dependent properties – (a) stiffness and (b) damping.

- K_p = pad stiffness (N/m)
- C_p = pad viscous damping (Ns/m)
- K_1 = frequency-dependent stiffness (N/m)
- K_2 = frequency-independent stiffness (N/m)
- C_1 = frequency-dependent viscous damping (Ns/m)
- α = stiffness fractional coefficient and $\alpha = \frac{\omega^2}{\omega^2 + z^2}$
- β = damping fractional coefficient and $\beta = \frac{z^2}{\omega^2}$

where ω is the radial frequency (s^{-1}), $\omega = 2\pi f$; and z is the partial inverse loss value (s^{-1}), $z = K_1/C_1$ (de Man, 2002).

2.3 Vibration measurement

To measure the vibration response of the rail pads, an accelerometer was placed on the top surface of the upper segment, as illustrated in figure 5. The mass of the upper segment is 30.30 kg, and the mass of each preloading bolt is 0.75 kg.

It should be noted that a test rig was rigidly mounted on a "strong" floor (1.5 m deep of heavily reinforced concrete), the frequency responses of which are significantly lower than those of interest for the rail pads. The floor also isolates ground vibration from surrounding sources. To impart an excitation on the upper mass, an impact hammer was employed within a capable frequency range of 0-3500 Hz. The FRF could then be measured by using PCB accelerometer connected to the Bruel&Kjaer PULSE modal testing system, and 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 system. The coherence function represents the quality of FRF measurements and should be close to unity.

2.4 Optimisation

Parts of FRFs, especially in the vicinity of the resonant frequencies, provide detailed information on the properties of the tested component. Using a curve-fitting approach achieves these dynamic properties. For this approach, the theoretical FRF from equation

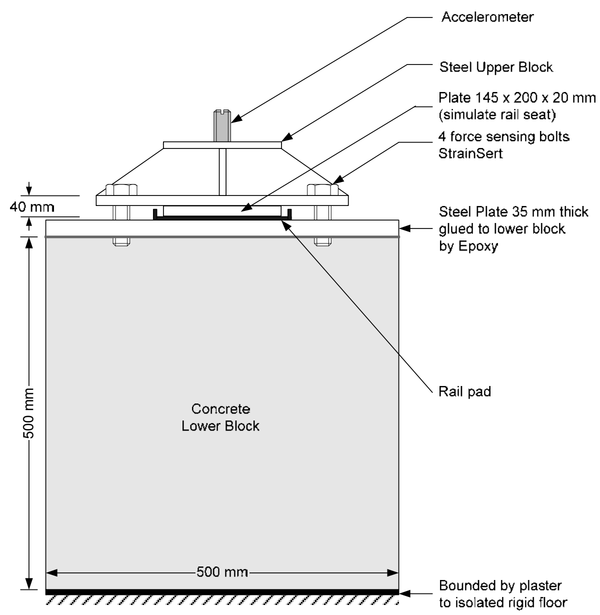

Figure 5: Schematic body diagram of the innovative rail pad tester developed at UoW.

(2) will be tuned to be as close as possible to the experimental FRF in a frequency band around the resonant frequency. The dynamic properties can be obtained from the optimisation. The correlation index (r^2) is the target function, while each parameter will be utilised in the least square algorithm as the objective solutions.

Iterations will converge when the residual tolerance of the objective parameters is less than 10^{-3}. Curve-fitting routines can be found in many general mathematical computer packages (eg. MATLAB, Mathematica, Maple), or using specialised curve-fitting computer codes (eg. DataFit).

3 EXPERIMENTAL OVERVIEW

3.1 Pad specimens

It should be noted that the innovative pad tester, as shown in figure 5, is capable of testing all standard sizes of rail pads. In this study, two types of unused rail pads are chosen (figure 1) for demonstration, including HDPE and studded rubber pads. These rail pads have kindly been supplied by the manufacturer (PANDROL) in Australia. Based on the information available from the manufacturer, it is found that the dynamic stiffness of HDPE pads is in the range of 700 to 900 MN/m, while the dynamic stiffness of studded rubber pads is about 45-65 MN/m. It should be noted that the available data from industry are associated with the rail pad type testing setup and specific loading regime, as prescribed in AS1085.19 (Standards Australia, 2001).

Table 2 gives the general data of the pad specimens. These two specimens of rail pads are the available types, which are commonly used in Australian railway networks for either passenger or heavy haul rolling stocks, ie. Sydney Suburban Network, Queensland Rails' tracks, Victoria urban and suburban lines, etc.

3.2 Modal testing

The test rig has been designed to apply preloads up to a maximum of approximately 400 kN in total. Each calibrated force-sensing bolt is connected to real-time data logger and to computer. Using four force-sensing bolts (StranSert), the preloading can be read, adjusted and recorded through a computer screen. In this study, the preload amount of 20 kN is applied to the rail pads. It should be noted that the preload of 20 kN is equivalent to average preload of the PANDROL e-Clip fastening system on the rails (Esveld, 2001).

The upper mass was impacted using an instrumented hammer. The accelerometer measured the responses and captured them to PULSE Dynamic Analyzer. Then, FRFs could be obtained. As an example, the properties of the PANDROL resilient rubber pad (studded type, 10 mm thick) were determined using the test rig and the results are presented in figure 6. They included: the magnitude FRF (figure 6(a)) and the coherence function (figure 6(b)) that confirmed a high degree of linearity between input and output signals. Parameter optimisation was then applied to the experimental FRFs, yielding the dynamic properties of rail pads under various conditions, see details in Remennikov & Kaewunruen (2005) and Kaewunruen & Remennikov(2006; 2008).

4 MODAL RESULTS

The resonant frequencies and corresponding dynamic properties of HDPE and rubber pads are presented in table 3. The results at preload of 20 kN are comparable to the previous research results tested by the Track Testing Center (TTC) of Spoomet, South Africa, by TU Delft (DUT) of the Netherlands, and by the UoW (Van't Zand, 1993; Remennikov & Kaewunruen, 2006). It should be noted that the correlation index (r^2) is the quality indicator of the best fit or, on the other hand, it implies the error of parameter estimation using the developed dynamic model.

Table 3 shows that, at 20 kN preloads, the resonant frequency of studded pad is remarkably less than that of HDPE rail pad. The state dependent results show the clear tendency of substantial increases in both frequency-dependent and frequency-independent dynamic stiffness, and damping values for the HDPE rail pads. It should be noted that the correlation indices (r^2) tends to be less than 4% error in the parameter optimisation.

Table 2: Dimensional data of rail pad specimens.

Type	Area (cm²)	Thickness (mm)	Shape
Studded rubber	267	10	Studded
HDPE	263	5.5	Plane

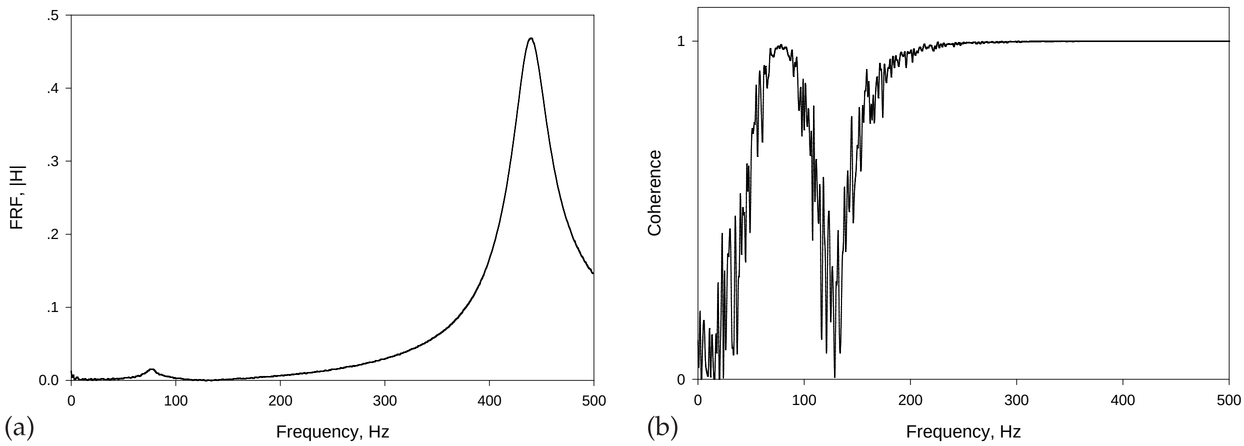

Figure 6: Frequency response function (a) and its coherence (b) of the tested studded rail pad under a preload of 20 kN.

Table 3: State dependent properties of new rail pads.

Type	k_2 (MN/m)	k_1 (MN/m)	c_1 (kNs/m)	f_r (Hz)	r^2
Rubber	209.01	210.14	3.0	440	0.9996
HDPE	1792.1	1141.0	4.1	795	0.9608

Table 4: State dependent properties of worn HDPE rail pads.

Years in services	k_2 (MN/m)	k_1 (MN/m)	c_1 (kNs/m)	f_r (Hz)	r^2
18	653.50	875.40	3.5	725	0.9359
20	297.81	1138.3	1.5	771	0.9851

A set of worn HDPE rail pads have been kindly provided by RailCorp, which were collected from Sydney suburban network (Remennikov et al, 2006). The pads were collected in different locations but on the same network line of rail track during the track re-conditionings. Variation of residual properties of aged rail pads depends on many factors, eg. contact stiffness, misalignments, fasteners, etc. Also due to the limitation of samples, the average results will be rather discussed in this paper. Using the identical testing method, table 4 gives the state-dependent properties of worn HDPE rail pads.

The modal results of those worn pads show that by tendency the resonant frequencies of HDPE pads tend to reduce slightly in relation to years in service. However, the frequency-independent stiffness and damping coefficients diminish considerably, as depicted by figure 7. An estimate shows that the frequency-independent stiffness decreases at the rate of 70 MN/m per year, while the other stiffness slightly changes. Figure 8 shows that the damping coefficient degrades about 0.09 kNs/m each year of service.

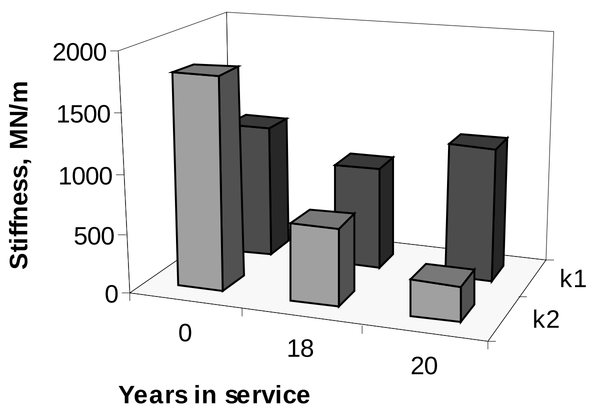

Figure 7: Dynamic stiffness.

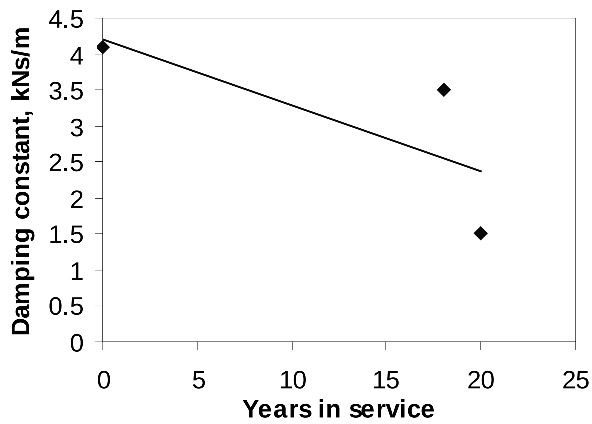

Figure 8: Dynamic damping.

5 CONCLUSION

An alternative rail pad tester based on the SDOF vibration response measurement for determining the dynamic properties of rail pads has been devised, as well as the state-dependent model of rail pads. The impact excitation technique has been efficiently employed to assess the dynamic stiffness and damping constant of HDPE and rubber rail pads available in Australia. The modal results demonstrate merit for an application to health monitoring of HDPE pads. It was found that the ages of rail pads have remarkable influence on dynamic stiffness. Also, it is evident that the frequency-independent stiffness of rail pads is more susceptible to the degradation of rail pads. The methodology of state-dependent model is applicable to dynamic health monitoring of rail pads. An analytical or numerical modelling of rail tracks can be accurately performed using the data obtained in this study. These state-dependent properties would enable the use of the modern track models in the future.

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SAKDIRAT KAEWUNRUEN

Sakdirat Kaewunruen (PhD, ME, BE Hons (Civil), GCert (Buss), MIEAust, CPEng, NPER, RPEQ) is currently a Senior Engineer in Track Engineering Department within Rail Corporation New South Wales in Sydney, Australia. He is a Chartered Professional Engineer, and has authored more than 60 publications in edited books, refereed journals and conferences. He has extensive experience in structural designs of concrete and steel structures, dynamic and impact analyses, railway track structures, wheel/rail interaction, structural risk and safety, ocean engineering, forensic engineering, and sustainable urban development. Recently, he was named the 2008 Young Railway Engineer of the Year by the Railway Technical Society of Australasia, Engineers Australia.

ALEX REMENNIKOV

Alex M Remennikov (PhD, BE Hons (Civil), MIEAust, CPEng, NPER) is a Senior Lecturer in Structural Engineering at the University of Wollongong. His research interests include analysis and design of structures subject to blast and impact loads, structural reliability, dynamics of railway track components, and the applications of energy absorbing materials for protecting critical infrastructure. He has over 100 technical publications in relation to his research interests. In addition, he has been involved in a variety of engineering consultancy projects for both governmental and private sectors, involving blast- and impact-resistant designs of structural systems, as well as earthquake designs of buildings and infrastructure facilities.