University of Wollongong
Research Online

Faculty of Engineering - Papers (Archive)

Faculty of Engineering and Information Sciences

1-1-2008

An alternative rail pad tester for measuring dynamic properties of rail pads under large preloads

Sakdirat Kaewunruen
University of Wollongong, sakdirat@hotmail.com

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

Follow this and additional works at: https://ro.uow.edu.au/engpapers

Part of the Engineering Commons

https://ro.uow.edu.au/engpapers/3945

Recommended Citation

Kaewunruen, Sakdirat and Remennikov, Alexander: An alternative rail pad tester for measuring dynamic properties of rail pads under large preloads 2008, 55-64.
https://ro.uow.edu.au/engpapers/3945

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au

Experimental Mechanics (2008) 48:55–64
DOI 10.1007/s11340-007-9059-3

An Alternative Rail Pad Tester for Measuring Dynamic Properties of Rail Pads Under Large Preloads

S. Kaewunruen · A.M. Remennikov

Received: 19 December 2006 / Accepted: 11 May 2007 / Published online: 13 June 2007
© Society for Experimental Mechanics 2007

Abstract One of the main components in ballasted railway track systems is the rail pad. It is installed between the rail and the sleeper to attenuate wheel/rail interaction loads, preventing the underlying railway sleepers from excessive stress waves. 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 effective preloading than anticipated in the past. On this ground, this paper highlights the significance of accounting for effects of preloading on dynamic properties of polymeric rail pads. An innovative test rig for controlling preloads on rail pads has been devised. 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. Based on the impact-excitation responses, some of the selected rail pads have been tested to determine such modal parameters as dynamic stiffness and damping constants in the laboratory. The influence of large preloads on dynamic properties of both new and worn rail pads is demonstrated in this paper. Additionally, the design criteria, which has been used to take into account the influence of the level of preload on dynamic properties of generic rail pads, are discussed.

Keywords Rail pads · Dynamic stiffness · Damping · Preload · Experimental modal testing

Note: The authors' work in the references can be found electronically via UoW Research Online at URL http://ro.uow.edu.au

S. Kaewunruen (✉) · A.M. Remennikov
School of Civil, Mining, and Environmental Engineering,
University of Wollongong,
Wollongong, NSW 2522, Australia
e-mail: sakdirat@uow.edu.au

A.M. Remennikov
e-mail: alexrem@uow.edu.au

Introduction

A rail pad is a major track component used in ballasted railway tracks worldwide. It is mostly made from a polymeric compound, rubber, or composite materials. The rail pads are mounted on rail seats and designed to attenuate the dynamic stress from axle loads and wheel impact from both regular and irregular train movements. In accordance with the design and analysis, numerical models of a railway track have been employed to aid the track engineers in failure and maintenance predictions.

In general, the bogie burden (wheel load) from train passages and the rail fastening system impart dynamic and static preloading to the track, respectively. This wheel load pressing on the track causes local deformation and consequent preload on its components. The toe load (the force underneath the rail transferring to the rail pad) can escalate to as much as 150–200 kN when a wheel burn strikes the railhead [1] (Remennikov AM, Kaewunruen S, submitted for publication). In most situations, dynamic responses of the railway tracks are directly associated with noise and wear problems in railway track environments. The current numerical models or simulations of railway tracks mostly exclude the effect of preloading on the nonlinear dynamic behaviour of rail pads, although it is evident that preloading has a significant influence on dynamic rail pad properties that affect the dynamic responses of railway tracks [2–5]. The primary reason is

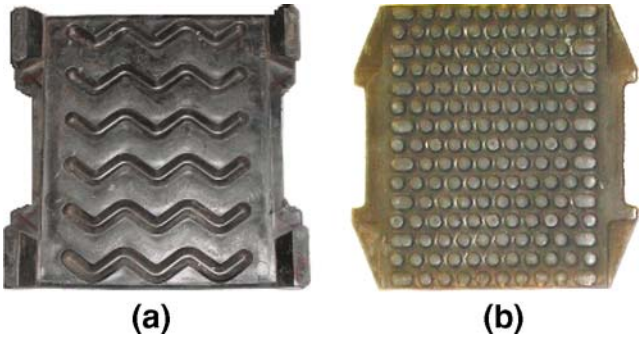


Fig. 1 Rail pad specimens. (**a**) HDPE 5.5 mm (**b**) studded 6.5 mm

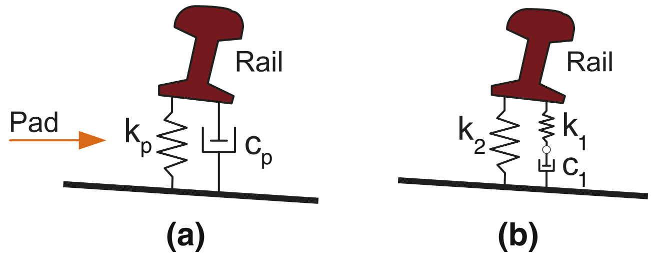


Fig. 2 Rail pad models. (**a**) Viscous damping model (**b**) state-dependent model

due to a lack of information, either about the dynamic characteristics of rail pads under variable preloads, or about the dynamic wheel-load distribution to rail pads and other track components. This paper presents an alternative rail pad tester for controlling large preloads. It also discusses the experimental results obtained as part of the railway engineering research activities at the University of Wollongong (UoW) aimed at improving the dynamic performance of railway tracks in Australia. The proposed relationships could be incorporated into track analysis and design tools for a more realistic representation of the dynamic load transfer mechanisms in railway tracks.

There are currently 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 and distinctive engineering properties. Figure 1 features the selected types of pads, namely the HDPE and studded-profile rail pads. The dynamic behaviour of rail pads is generally represented by two important parameters: dynamic stiffness and damping coefficient. Sometimes, more variables are needed and a nonlinear dynamic model or so-called 'state-dependent viscoelastic model' might be adopted. To obtain such properties, the dynamic testing of rail pads in the laboratory or on the track is required. From the dynamic response measurements, both linear and nonlinear properties can be estimated by optimizing the objective formulations of the desired dynamic model. Modeling rail pads as a 'spring and viscous dashpot in parallel' seems to be a very practical means for the railway industry. The parameters can be obtained conveniently, and this model is often applied to various studies on vertical vibrations of railway tracks [1, 2, 6, 7].

The state-dependent model of rail pads, where an additional spring is presented in series with the dashpot, as illustrated in Fig. 2, has been recently proposed but the interpretation of the mathematical model and its influence on the dynamic responses of a track are unclear and need further investigation [8–11]. Alternatively, De Man [9] noted a benefit of the state-dependent models in that the model can separate influences of loading frequency from the influences of preload, in the case of harmonic or cyclic testing on frequency-dependent materials. With regard to identifying the properties of the track components, e.g. rail pads, Grassie and Cox [2] recommended that the best way to determine the dynamic parameters is by extracting from operational vibration measurements or field testing by an impact hammer or dynamic exciter. It should be noted that the dynamic properties could only be determined at the resonant frequency, when using an impact hammer.

A number of publications have recently addressed the dynamic characteristics of resilient pads (Remennikov AM, Kaewunruen S, 2006, submitted for publication) [11–19]. It is noted that some studies included a two-degree-of-freedom (2DOF) rail pad model [20–22]. With the exception of the work of Maes et al. [11], which measured the input acceleration directly, the technique of 'indirect measurement' is generally utilised. Indirect measurement is an approach that measures the dynamic responses due to dynamic input force or excitation. The direct method can be used when the test specimens are very small and the exciter is very powerful. A variety of previous rail pad testers are illustrated in [11]. The preload capacities (limited ranges of applied preload) of those rail pad testers are presented in Table 1. It is found that the capacities of previous rail pad testers are limited. From the literature, the single-degree-of-freedom (SDOF) dynamic model of rail pads has been used in a number of investigations as well. The instrumented hammer impact technique is widely used in this kind of tests due to its proven effectiveness and mobility. Most of the above-mentioned studies discuss the effects of loading frequency that tend to induce potential problems to railway tracks (e.g., noise, wear, etc). It has been shown that the loading

Table 1 Review of current rail pad testers

Place	Excitation	Method	Model	Preload Capacity
TU-Delf [9, 13]	Impact	Direct	SDOF	0–25 kN
VUB-Belgium [11]	Harmonic	Direct	SDOF	0–1 kN
UNICAN-Spain [19]	Harmonic	Direct	SDOF	20–95 kN
TNO-UK [21]	Harmonic	Indirect	2DOF	0–80 kN
TU-Berlin [22]	Harmonic	Indirect	2DOF	0–95 kN
UoW-Australia	Impact	Direct	SDOF	0–400 kN

frequency may increase the dynamic stiffness of rail pads, and plays a significant role in the level of damping provided. However, the influence of large preloads, which might be induced by dynamic wheel/rail interaction, has not been studied adequately so far.

Employed in this study is a SDOF-based method that allows evaluation of the dynamic properties of rail pads. The instrumented hammer impact technique is adopted in order to benchmark with the field trials [23–25]. Figure 3 demonstrates a typical ballasted railway track. Figure 4 shows the schematic test setup of the rail pad tester developed at the University of Wollongong. This test rig takes the advantage of the modern force sensing bolt that can resist large loads up to 100 kN each. An analytical solution for a frequency response function was used to best fit the vibration responses. Vibration response records were obtained by impacting the upper segment with an instrumented hammer. In this paper, 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 the modal testing measurements. The demonstrations provided focus on both new and worn pads.

Analytical Modal Analysis

In this study, the rail pad is considered as the only elastic element in the test rig, as shown in Fig. 4. This test rig has been developed to perform indirect measurement of pad properties. A single degree of freedom (SDOF) system has been proven to be a suitable model for use in the determination of the dynamic characteristics of the rail pad [16]. The dynamic model of rail pads includes the following two parameters: dynamic stiffness and damping constant.

SDOF Dynamic Model

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

$$m_{\mathrm{p}}\ddot{x} + c_{\mathrm{p}}\dot{x} + k_{\mathrm{p}}x = f(t) \tag{1}$$

$$\omega_n^2 = k_p/m_{\mathrm{p}},\ 2\zeta\omega_n = c_{\mathrm{p}}/m_{\mathrm{p}},\ or\ \zeta = c_{\mathrm{p}}/2\sqrt{k_{\mathrm{p}}m_{\mathrm{p}}} \tag{2}$$

where m_{p}, c_{p}, and k_{p} generally represent the effective rail mass, damping and stiffness of a rail pad, respectively. By taking the Fourier transformation of equation (1), the frequency response function can be determined. The magnitude of FRF is given by

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

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

$$H(f) = \frac{1}{m_{\mathrm{p}}}\frac{4\pi^2\beta f^2}{\sqrt{\left[1 - 4\pi^2\beta f^2\right]^2 + \left[4\pi^2\beta\left(\frac{c_{\mathrm{p}}^2}{k_{\mathrm{p}}m_{\mathrm{p}}}\right)f^2\right]}} \tag{4}$$

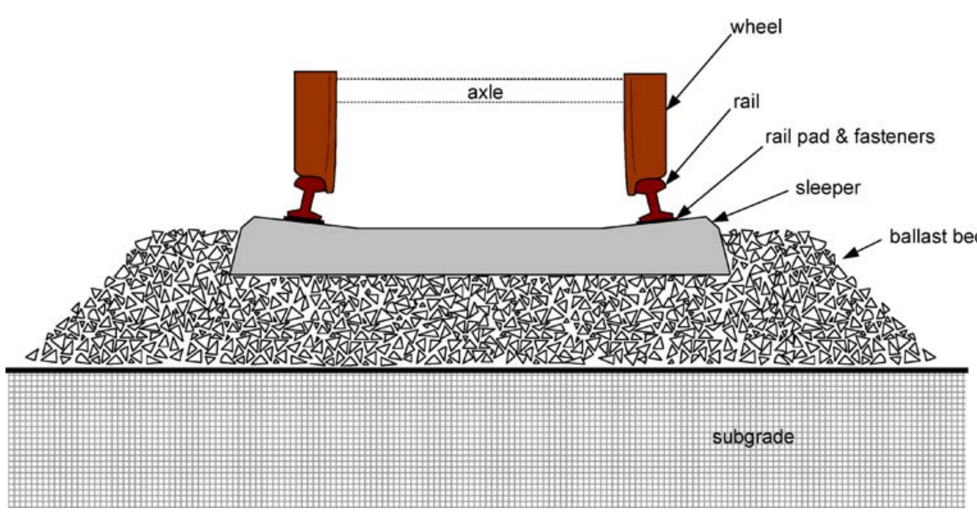


Fig. 3 Typical ballasted railway track

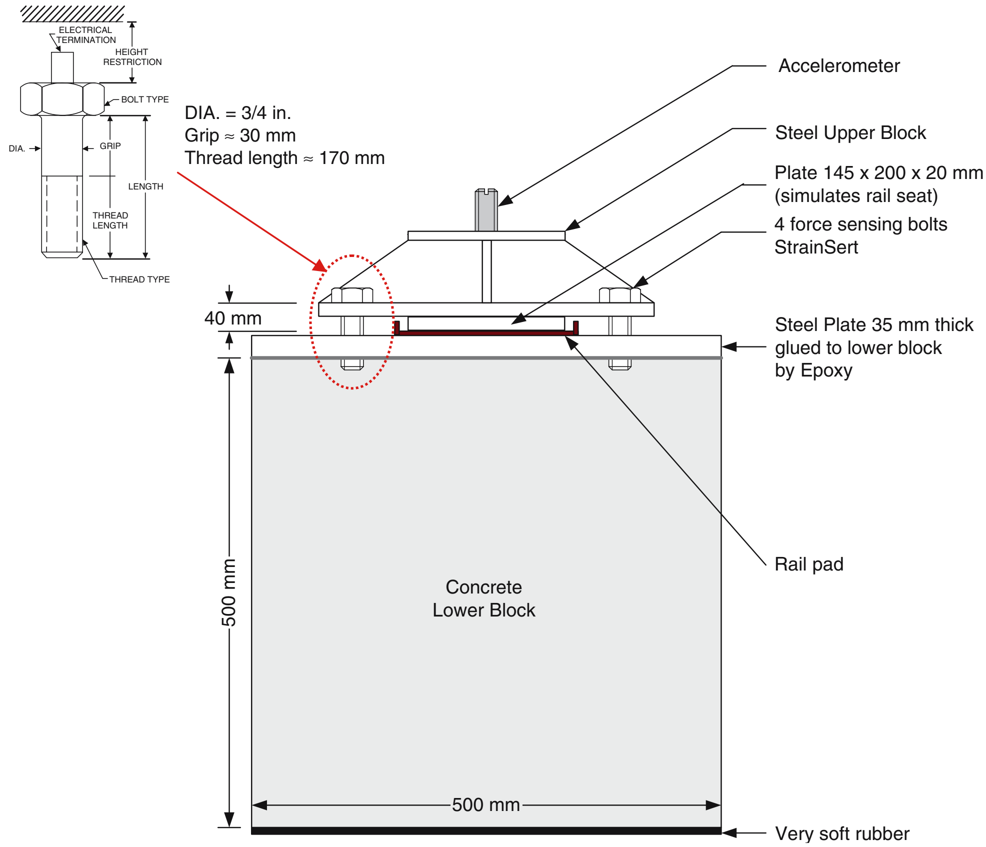


Fig. 4 Schematic diagram of the rail pad tester developed at UoW

where,

$$\beta = \frac{m_p}{k_p} \tag{5}$$

This expression contains the system parameters m_p, k_p and c_p that will later be used as the curve-fitting parameters.

Vibration Measurements

To measure the vibration response of the rail pads, an accelerometer was placed on the top surface of the upper segment, as illustrated in Fig. 4. 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" or "isolated" floor (1.5 m depth of heavily reinforced concrete), the frequency responses of which are significantly higher 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 0–3,500 Hz. The FRF could then be measured by using the PCB accelerometer connected to the Bruel&Kjaer Pulse modal testing system, and to a computer. Measurement records also included the impact forcing functions and the coherence functions.

Parameter Optimization

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 the dynamic properties can be extracted. In this approach, the theoretical FRF from equation (4) will be tuned to be as close as possible to the experimental FRF in a frequency band around the resonant frequency. Optimization algorithms were programmed using DataFit [26]. The dynamic properties can be obtained from the optimization. The correlation index (r^2) is the target function while each other parameter will be utilized 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}.

Alternative Rail Pad Tester

Design Attributes

A base-isolated experimental rig for dynamic testing of rail pads (so-called 'pad tester') has been developed at the University of Wollongong. As shown in Fig. 5, the test rig consists of a concrete block that supports a steel mass, preloading bolt system, and a rail pad. The concrete block is

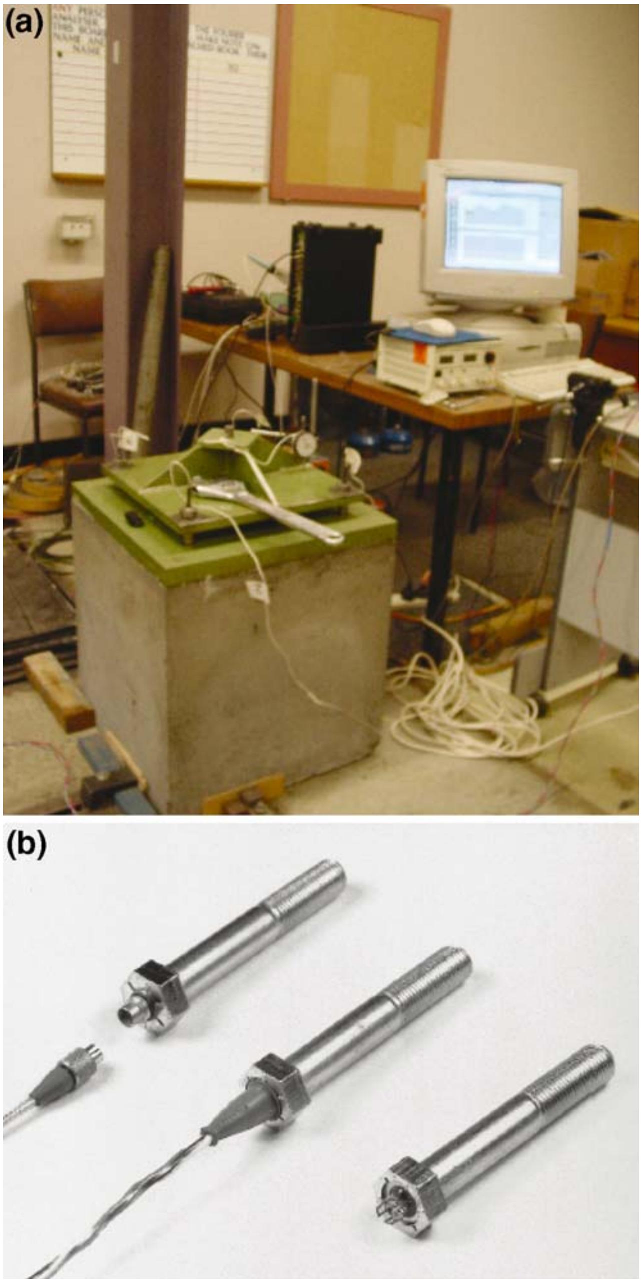


Fig. 5 The alternative rail pad tester. (**a**) Experimental setup (**b**) Examples of force sensing bolts

isolated from surrounding noise by placing it on a very soft rubber plate between the block and the strong floor representing the absolutely rigid foundation. The very soft rubber plate was chosen based on the 2DOF finite element analyses. The characteristics of the very soft rubber plate allow the upper block to vibrate freely but prohibit surrounding noise and dynamic interaction from the lower mass, as exemplified in Table 2. An accelerometer and dial gauges are installed on the upper steel mass, as illustrated in Fig. 5(a). An instrumented impact hammer is employed ten times to impart excitation to the assembly of components. The frequency response function (FRF) is then obtained using the Pulse dynamic analyser in the frequency range of interest, from 0 to 1,000 Hz. The coherence function is also obtained to evaluate the quality of FRF measurements, which are averaged from the ten hits.

Preload Control

The test rig was designed to apply preloads up to a maximum of approximately 400 kN in total. Each calibrated force-sensing bolt is connected to a real-time data logger and to a computer [see Fig. 5(a) and (b)]. Using four force-sensing bolts (StranSert), the preloading can be introduced, incrementally adjusted and recorded through a computer screen. Ten levels of preload of rail pads in the range between 0 to 200 kN were considered. Dynamic performance of rail pads under this large amount of preload has not been investigated to date. It should be noted that the preload of 20 kN is equivalent to an average preload of the Pandrol e-Clip fastening system on the rail. Also, the preload of 200 kN is comparable to a 40-ton axle load [27], which is quite rare. In general, the static weight of such a huge axle load would exert a static rail seat load (i.e. to the pad) of about 110 kN. However, that rail seat load could rise to 200 kN at times if quasi-static (dynamic ride) force variations are included.

Modal Testing

The upper mass was impacted using an instrumented hammer. The accelerometer was used to measure the vibration response, which would later be processed by the Pulse Dynamic Analyzer to produce FRFs. 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 Fig. 6. Parameter optimization was then applied to the experimental FRFs, yielding the dynamic properties of rail pads under various conditions [16].

Applications

Determination of Dynamic Rail Pad Characteristics

All standard sizes of rail pads can be tested using the developed rail pad tester. Two types of new rail pads were chosen (Fig. 1), which included the high-density polyethylene (HDPE) and studded rubber pads. As supplied by the manufacturer (Pandrol), the dynamic stiffness of HDPE pads ranges between 700 and 900 MN/m, while the dynamic stiffness of studded rubber pads is about 45–65 MN/m. Table 3 gives the general data of the pad specimens. These two specimens of rail pads are the types widely used in Australian railway networks for either passenger or heavy haul rolling stocks, i.e. Sydney Suburban Network, Queensland Rails' tracks, etc. In this case study, the testing procedures are identical to those described above. The influence of large preloads on the dynamic behavior of new rail pads is highlighted in this investigation.

Monitoring Deterioration of Worn Pads

The worn rail pads were collected from a railway network operated by Rail Corporation (RailCorp) in areas of New South Wales, Australia. Two groups of used rail pads, after 99 MGT (18 years in service) and 110 MGT (20 years in service), were evaluated. Figure 7 shows the samples of aged pads (HDPE 5.5 mm) used in this study. New pads of the same type, provided by Pandrol Australia, were tested using identical techniques. The innovative rail pad tester can be used to trace and monitor the deterioration of worn rail pads on the modal data basis. This paper presents unprecedented results of the dynamic behaviour of worn pads under large preloads. These findings will result in the improvement of track maintenance and renewal in Australia [17, 23, 24].

Experimental Results

Variations of the incremental preload during excitation have been statistically detected for about 1–4% of each instant preload during the tests. The excitation was given through the impact hammer and the frequency response function was obtained using PULSE after each preloading. The load–deflection curve was recorded using Dial Gauges, for instance as shown in Fig. 8. Figure 9 shows the examples of curve fitting using DataFit.

Characteristics of New Rail Pads

The resonant frequencies and corresponding dynamic properties of HDPE and rubber pads are presented in Fig.

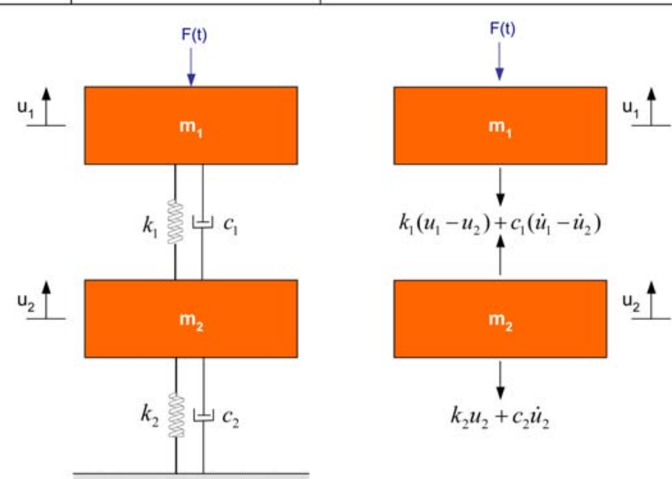
Table 2 2DOF finite element model and parametric analyses

Rubber base stiffness MN/m	Natural frequency, Hz.		Type of Rail Pad
	First resonance	Second resonance	
0.01	1.42	286.06	**Studded Pad**
0.10	4.49	286.06	
1.00	14.19	286.14	k_1 = 65 MN.m
10.00	44.73	286.95	c_1 = 5.5 kNs/m
100.00	136.57	297.22	
0.01	1.42	883.45	**HDPE Pad**
0.10	4.49	883.45	
1.00	14.19	883.48	k_1 = 620 MN.m
10.00	44.85	883.73	c_1 = 3.0 kNs/m
100.00	141.43	886.36	

Note that:

For rubber base parameters
c_2 = 10 kNs/m

FEM model is illustrated:
m_1 = 25 kg
m_2 = 75 kg



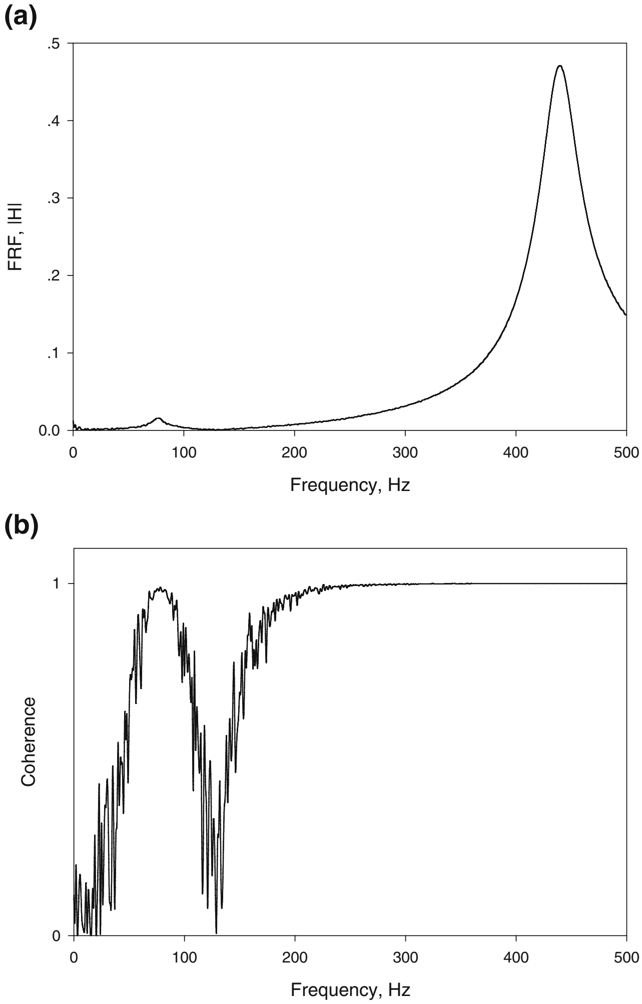


Fig. 6 Frequency response function and its coherence of the tested studded rail pad under a preload of 20 kN. (**a**) FRF, (**b**) coherence

Fig. 7 Worn rail pads (**a**) after 99 MGT in service on RailCorp track, (**b**) after 110 MGT in service on RailCorp track

10. The results at preload of 20 kN are comparable to the previous experimental results published by the Track Testing Center (TTC) of Spoomet, South Africa, and by TU Delft (DUT) of The Netherlands [13]. The correlation indices are found to have less than 2% error.

It can be seen from Fig. 10(a) that at low to moderate levels of preload, the effect of preloading on resonant frequencies of the studded pad is significant. This effect fades away when the preload exceeds 100–150 kN. Figure 10(b) and (c) show the tendency of substantial increases in both dynamic stiffness and damping values with incremental preloads. On the other hand, Fig. 10 also demonstrates that only very low preloads have an effect on resonant frequencies and corresponding dynamic characteristics of the HDPE pads. At moderate to high levels of preload, the preloading seems to have a small influence on the dynamic stiffness and no impact on either resonant frequencies or damping coefficients.

Resonant frequencies of the studded rubber pads tend to be less than those of the HDPE pads at low to moderate preloads. However, at high preloads, the effect of preloading on the resonant frequencies seems to be significantly less, resulting in similar values of the natural frequencies. Although the studded pads have lower dynamic stiffness than the HDPE pads at low levels of preloading, they are likely to gain benefit from high preloads and become considerably stiffer. Interestingly, the damping mechanism of studded rubber pads is susceptible to incremental preloads, whilst in the HDPE pads the damping mechanism needs a certain level of preload to drive the full mechanism and is therefore not sensitive to any further preloads.

Table 3 General data of rail pad specimens

Type	Area (cm^2)	Thickness (mm)	Shape
Studded rubber	267	10	Studded
HDPE	208	5.5	Plane

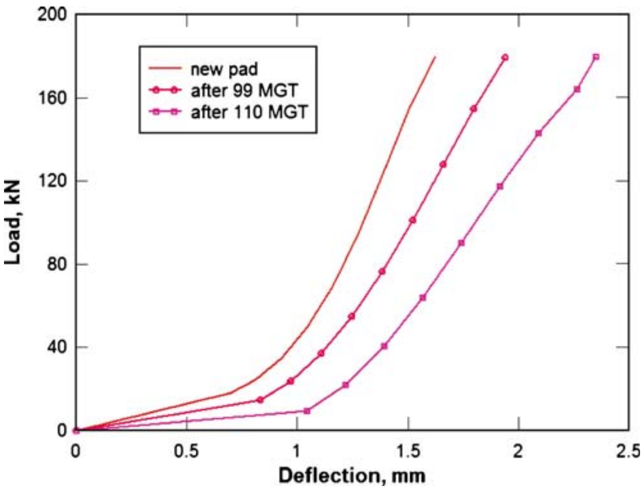


Fig. 8 Load–deflection curves of worn rail pads

Characteristics of Worn Rail Pads

Both new and worn pads had incremental preloads applied to them. By means of force sensing bolts, the static behaviors of rail pads can be determined. The nonlinear load deflection curves were found as shown in Fig. 8. The curves imply that the stiffness of rail pads increases with static preload as the slope of the curve becomes much steeper in the large loading region. However, when comparing worn pads, it can be seen that the stiffness reduces with the age of the pad. New pads seem to have the highest energy absorption capacity, while the level of the energy absorption diminishes with the age of used rail pads.

Figure 11(a) shows the resonant frequencies of rail pads. It is clearly found that the resonant frequencies of the older pad are slightly lower than the younger ones. Figure 11(b) and (c) shows the determined dynamic stiffness and damping of worn rail pads under preloads using the curve fitting approach. The maximum correlation indices of curve fitting were found to have less than 4% error for all pads.

It appears that the stiffness and damping coefficients of aged pads are gradually reduced. The relationships between resonant frequency and preload, and between dynamic stiffness and preload are promising. At this stage, the aged pad data are available only for three different ages. Using linear regression analysis for the results at 20 kN preload, the dynamic stiffness can be estimated to deteriorate at the rate of about 2.18 MN/m per 1 MGT (or 12 MN/m per year), while the damping value reduces at about 19.63 Ns/m per 1 MGT (or 108 Ns/m per year) [16]. However, it can be seen that the damping values fluctuate in a limited range. This is because the aged rail pads have been compressed greatly from long service and consequently they are stiff but worn. It is also found that once the preloading is high enough, its influence on the damping constant of this type of rail pad becomes insignificant. These findings will be further investigated by a more comprehensive study of rail pads of different ages in the near future.

Conclusion

An alternative, innovative rail pad tester based on the SDOF vibration response measurement for determining the dynamic properties of rail pads subjected to large preloads has been devised. The impact excitation technique has been

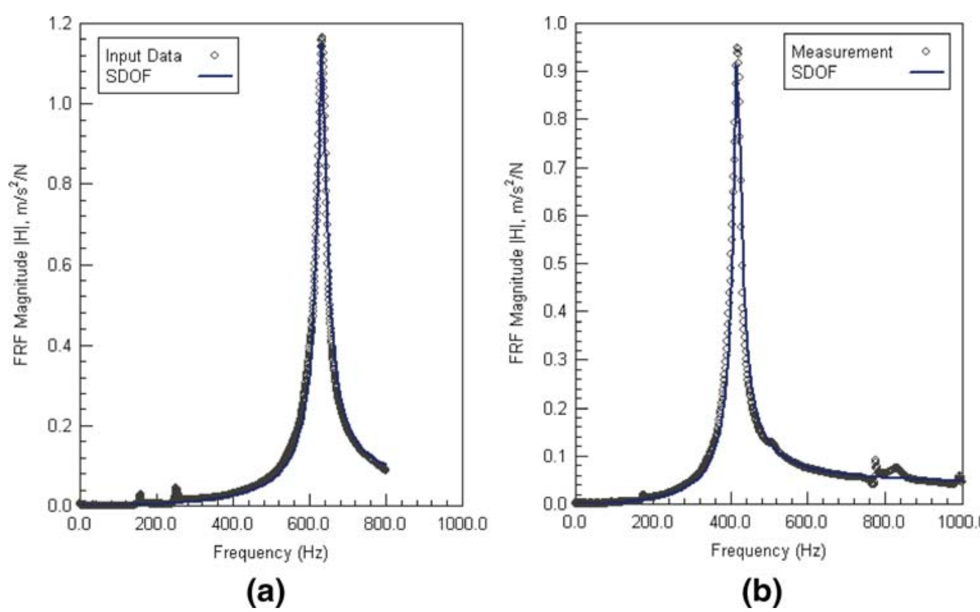


Fig. 9 Curve fitting of frequency response functions at 20 kN preload, (**a**) new pad, (**b**) worn pad (99MGT)

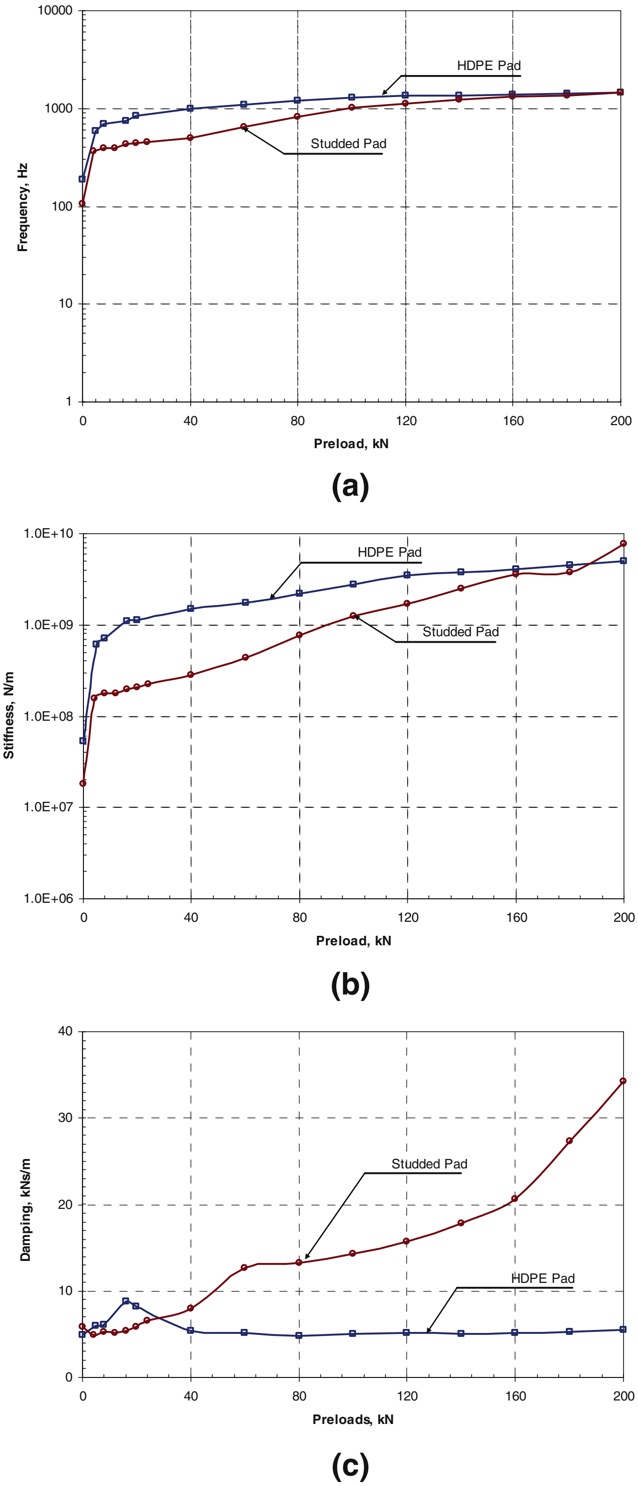


Fig. 10 Dynamic behaviors of new rail pads under large preloads. (**a**) Effects of preloading on resonant frequencies, (**b**) dynamic stiffness, (**c**) and damping values

found to be a simple, reliable, fast and non-destructive test method for assessing the dynamic stiffness and damping constant of all kinds of rail pad types available in Australia. This approach enables testing of new types of rail pads as well as identification of the influences of incremental preloading on their dynamic characteristics. It has been found that the preloads could have significant influence on the natural frequencies and the corresponding dynamic

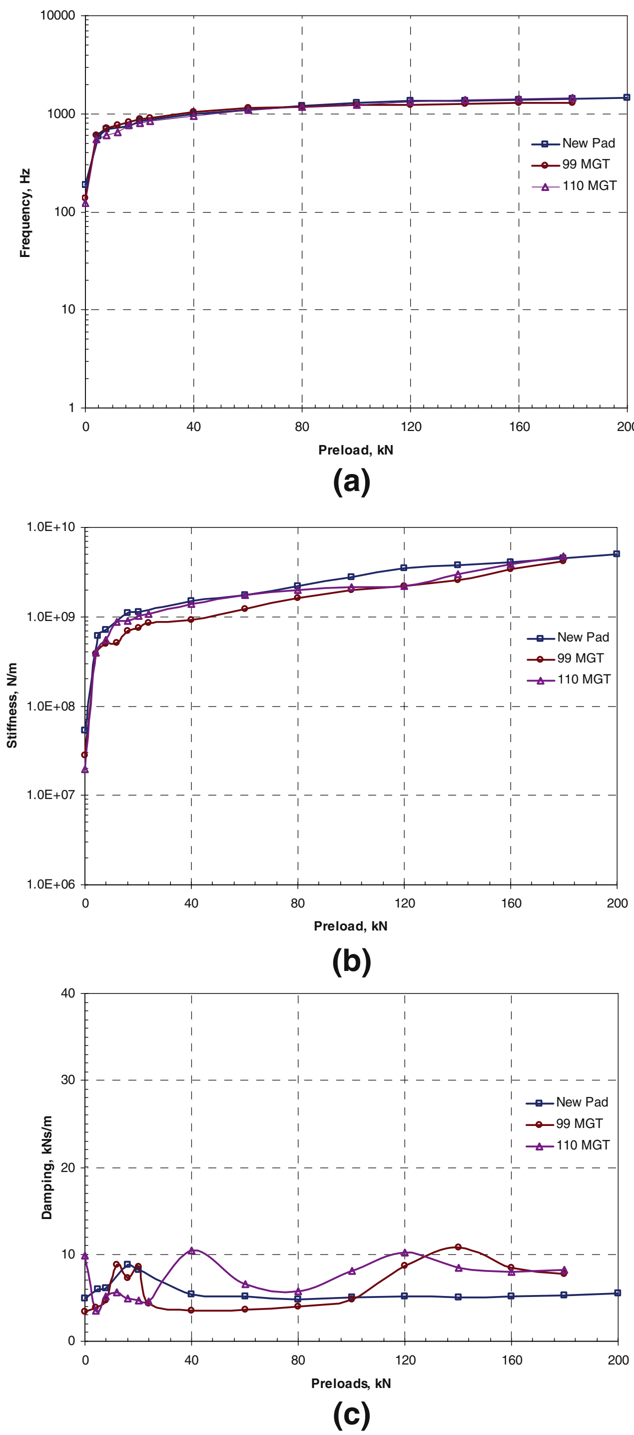


Fig. 11 Dynamic behaviors of worn rail pads under large preloads. (**a**) Resonant frequencies, (**b**) dynamic stiffness, (**c**) and damping values

properties of the studded rubber pads. It has also been demonstrated that the damping mechanism of the studded rubber pads is much more susceptible to preloads than that of the HDPE pads.

Dynamic properties of structural/mechanical components can be used for a number of applications to railway track dynamics such as analysis, modeling, and, as presented in this paper, monitoring the structural degradation rate. Also presented in this paper are applications of the test rig, together with experimental modal testing to determine and monitor the structural degradation rate of rail bearing pads. The dynamic characteristics of rail pads, such as resonant frequency, dynamic stiffness, and damping values, have been highlighted. Based on the linear regression of the results, it can be approximated that the per-MGT rate of rail pad degradation in terms of dynamic stiffness is about 2.18 MN/m and the rate for the damping is approximately 19.63 Ns/m. It should be noted that this type of pad is a high-density polyethylene (HDPE) pad with 5.5 mm thickness. Nonetheless, this information is imperative to track maintenance and renewal divisions in order to make decisions and plan optimum track implementation. In addition, RailCorp Sydney NSW and Queensland Rail agree to provide the University of Wollongong more worn pads for further investigations. Further investigation about the condition assessments of a variety of rail pads with different ages, the degradation rates, and the optimum renewal period will be presented in the near future.

Acknowledgement The authors gratefully acknowledge the Australian Cooperative Research Centre for Railway Engineering and Technologies (Rail-CRC) for the financial support. New rail pads are kindly provided by Pandrol (Australia) Co Ltd. Worn rail pads are kindly provided by Karl Ikaunieks of RailCorp, Sydney NSW (Australia). Many thanks go to Alan Grant for the laboratory assistance. The assistance from the Learning Development Centre (UoW) is also appreciated.

References

1. Cai Z (1992) Modelling of rail track dynamics and wheel/rail interaction. Ph.D. Thesis, Department of Civil Engineering, Queen's University, Ontario, Canada.
2. Grassie SL, Cox SJ (1984) The dynamic response of railway track with flexible sleepers to high frequency vertical excitation. Proc Inst Mech Eng Part D 24:77–90.
3. Wu TX, Thompson DJ (1999) The effects of local preload on the foundation stiffness and vertical vibration of railway track. J Sound Vib 215(5):881–904.
4. Kaewunruen S, Remennikov A (2006) Sensitivity analysis of free vibration characteristics of an in-situ railway concrete sleeper to variations of rail pad parameters. J Sound Vib 298(1–2):453–461.
5. Kaewunruen S, Remennikov AM (2007) Effect of improper ballast tamping/packing on dynamic behaviors of on-track railway concrete sleeper. Int J Struct Stab Dyn 7(1):167–177.
6. Knothe K, Grassie SL (1993) Modelling of railway track and vehicle/track interaction at high frequencies. Veh Syst Dyn 22 (3–4):209–262.
7. Oscarsson J (2002) Dynamic train-track interaction: Variability attributable to scatter in the track properties. Veh Syst Dyn 37(1):59–79.
8. Fenander, A (1998) A fractional derivative railpad model included in a railway track model. J Sound Vib 212(5):889–903.
9. De Man AP (2002) DYNATRACK: A survey of dynamic railway track properties and their quality. Ph.D. Thesis, Faculty of Civil Engineering, Delft University of Technology, The Netherlands.
10. Nielsen JCO, Oscarsson J (2004) Simulation of dynamic train-track interaction with state-dependent track properties. J Sound Vib 275:515–532.
11. Maes J, Sol H, Guillaume P (2006) Measurements of dynamic railpad properties. J Sound Vib 293(3–5):557–565.
12. Grassie SL (1989) Resilient railpads: their dynamic behavior in the laboratory and on track. Proc Inst Mech Eng Part F J Rail Rapid Transit 203:25–32.
13. Van't Zand J (1993) Assessment of dynamic characteristics of rail pads. Railw Eng Int 1994 Edn 23(4):15–17.
14. Kaewunruen S, Remennikov A (2005) Application of experimental modal testing for estimating dynamic properties of structural components. Proceedings of Australian Structural Engineering Conference 2005, Sep 11–14, Newcastle, Australia [CD Rom].
15. Kaewunruen S, Remennikov A (2005) Monitoring structural degradation of rail bearing pads in laboratory using impact excitation technique. Proceedings of the 1st International Conference on Structural Condition Assessment, Monitoring, and Improvement, Dec 12–14, Perth, Australia, pp 389–394.
16. Remennikov A, Kaewunruen S (2005) Determination of dynamic properties of rail pads using instrumented hammer impact technique. Acoust Aust 33(2):63–67.
17. Remennikov A, Kaewunruen S, Ikaunieks K (2006) Deterioration of dynamic rail pad characteristics. Conference of Railway Engineering 2006, Apr 30–May 3, Melbourne, Australia, 173–179.
18. Kaewunruen S, Remennikov A (2006) Laboratory measurements of dynamic properties of rail pads under incremental preload. Proceedings of the 19th Australasian Conference on the Mechanics of Structures and Materials, Nov 29–Dec 1, Christchurch, New Zealand, [CD Rom].
19. Carrascal IA, Casado JA, Polanco JA, Gutierrez-Solana F (2007) Dynamic behavior of railway fastening setting pads. Eng Fail Anal 14(2):364–373.
20. Fenander A (1997) Frequency dependent stiffness and damping of railpads. Proc Inst Mech Eng Part F J Rail Rapid Transit 211:51–62.
21. Thompson DJ, van Vliet WJ, Verheij JW (1998) Developments of the indirect method for measuring the high frequency dynamic stiffness of resilient elements. J Sound Vib 213(1):169–188.
22. Knothe K, Yu M, Ilias H (2003) Measurement and modelling of resilient rubber rail-pads. In: Popp K, Schiehlen W (eds) System dynamics and long-term behaviour of railway vehicles, track and subgrade. Springer, Berlin, Germany, pp. 265–274.
23. Kaewunruen, S., Remennikov, A. (2006) Non-destructive evaluation for dynamic integrity of railway track structure. Proceedings of International Conference on Structural Integrity and Failure-SIF2006, Sep 27–29, Sydney, Australia, 294–299.
24. Kaewunruen S, Remennikov AM (2006) Non-destructive testing (NDT): a tool for dynamic health monitoring of railway track structures. Mater Aust 39(6):14–16.
25. Kaewunruen S, Remennikov AM (2007) Field trials for dynamic characteristics of railway track and its components using impact excitation technique. NDT & E International, in press.
26. DataFit (2005) User's Manual, Oakdale Engineering, Oakdale, PA, USA.
27. Esveld C (2001) Modern railway track, 2nd edn. MRT-Productions Press, The Netherlands, p. 653.