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Laboratory measurements of dynamic properties of rail pads under incremental preload

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Laboratory measurements of dynamic properties of rail pads subjected to incremental preloads

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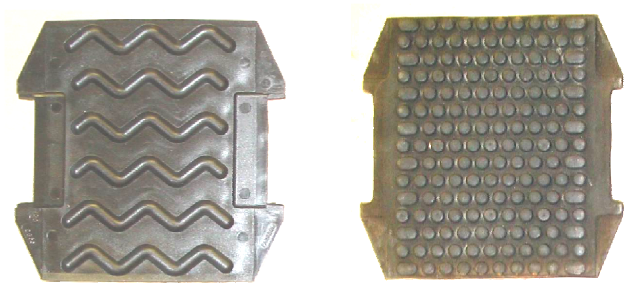
ABSTRACT: Rail pad is an important component in ballasted railway track. Its main function is to attenuate track loads, preventing underneath railway sleepers from excessive stress waves. Generally, the dynamic track design relies on the available data that are mostly focused on the condition at a specific toe load. Recent findings show that track irregularities appreciably amplify the loads over railway tracks. This nature of traffics gives rise to a considerable concern that the rail pad undergoes higher effective pre-loading than anticipated in the past. On this ground, this paper highlights the significance of pre-loading on dynamic properties of polymeric rail pads. An innovative test rig for controlling preloads on rail pads has been developed. Based on single-degree-of-freedom impact-excitation responses, the rail pads, which have been subjected to incremental preloads, are tested for their modal parameters such as dynamic stiffness and damping constants in laboratory. The influence of large preloads on dynamic properties of the rail pads is portrayed. The further discussion also involves the approach to adopt the relationships between dynamic properties versus preloading variations in practical uses.

1 INTRODUCTION

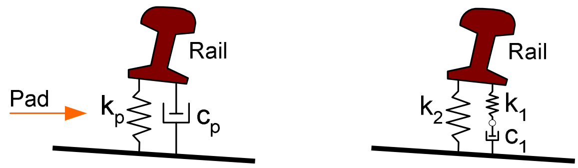
Rail pad is a major track component usually used in ballasted railway tracks worldwide. It is mostly made from polymeric compound, rubber, or composite materials. Mounted on rail seats, rail pads are aimed at attenuating the dynamic stress from axle loads and wheel impact from both regular and irregular train movements. In terms of design and analysis, numerical models of a railway track have been employed to aid track engineers in failure and maintenance predictions. Apparently, the bogy burden or wheel passing and the fastening system impart dynamic and static preloading to the track, respectively. Nonetheless, the current numerical models or simulations of railway tracks mostly exclude the effect of preloading on the nonlinear dynamic behavior of rail pads, although it is evident that preloading has significant influence on dynamic rail pad properties that affect the dynamic responses of railway tracks (Grassie and Cox, 1984; Wu and Thompson, 1999). The primary reason is due to the lack of either information on the behaviors of dynamic characteristics of rail pads under variable preloads, or knowledge of the dynamic wheel-load distribution to rail pads and other track components. This paper discusses the practical data that meet the deficiency of the dynamic rail pad behavior data, while the recent railway research at the University of Wollongong (UoW) has been preparing to address the dynamic and impact load transfer problem. This data could be incorporated into the development of a component module in the update nonlinear real-time modeling of a railway track in the future.

It should be noted that dynamic responses of the track directly relate to noise and wear levels of railway tracks. Currently, 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. Figure 1 illustrates the examples of HDPE and studded-profile rail pads. Dynamic behaviors of rail pads are normally presented into two important values: dynamic stiffness and damping coefficient. Sometimes, more variables are needed and nonlinear dynamic model or so-called '*state-dependent viscoelastic model*' might be adopted. 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 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 railway industry. Not only can the parameters be obtained conveniently, this model is usually applied to the studies on vertical vibrations of railway tracks (Grassie and Cox, 1984; Cai, 1992; Knothe and Grassie, 1993; and Oscarsson, 2002). The state-



a) HDPE b) Studded

Figure 1. Rail pad specimens



a) viscous damping model b) state-dependent model

Figure 2. Rail pad models

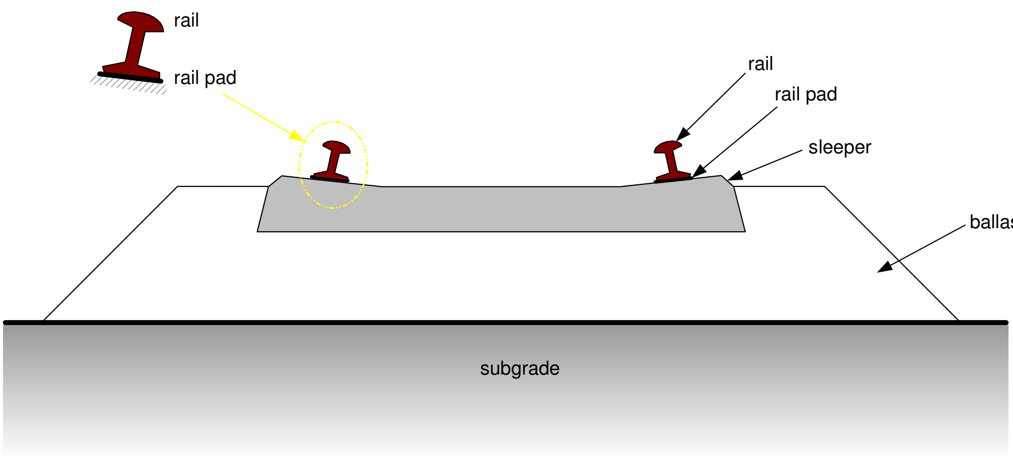


Figure 3. Typical ballasted railway track (Remennikov and Kaewunruen, 2005)

dependent model of rail pads, where an additional spring is presented in series with the dashpot as illustrated in Figure 2, is recently proposed but the interpretation and representation of the mathematical model and its impact to dynamic responses of a track are unclear and need further attention (Fenander, 1998; de Man, 2002; Neilsen and Oscarsson, 2004; Maes et al., 2006). Alternatively, 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. Regarding to identify properties of the track components e.g. rail pads, Grassie and Cox (1984) recommended that it be the best way to determine dynamic parameters by extracting from operational vibration measurement or field testing by an impact hammer or dynamic exciter. It should be noted that the dynamic properties could only be determined at the resonance frequency, when using an impact hammer.

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 and 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). Except Maes's work that measured the input acceleration directly, the technique of '*indirect measurement*' has been utilized. Indirect measurement is a way that measures output responses to dynamic input force or excitation. The direct method is possible to use when the test specimens are very small and the exciter is very powerful. From the literature, single-degree-of-freedom (SDOF) dynamic model has been applied to the setup of a number of investigations. Instrumented hammer impact technique is of very wide uses in this kind of tests due to its proven effectiveness and mobility. The results indicated the emphases of those investigations that are placed on effects of frequency, small preload, and ages. Most of studies discussed mainly the effects of loading frequency, which tends to induce consequent problems to railway tracks, i.e. noise, wear, etc. It has showed that the loading frequency slightly increases the dynamic stiffness of rail pads, and plays dramatic role on the damping. However, the influence of large preload has not been mentioned adequately elsewhere.

In this paper, a SDOF-based method was developed to evaluate the dynamic properties of rail pads. Instrumented hammer impact technique is adopted in order to benchmark with the field trials (Kaewunruen and Remennikov, 2005c). Figure 3 demonstrates a typical ballasted railway track and Figure 4 shows the schematic test setup of an innovative rail pad tester developed at University of Wollongong. An analytical solution was used to best fit the vibration responses. Vibration response recordings were obtained by hitting the rail with an instrumented hammer. In this paper, the effective mass, dynamic stiffness and damping of resilient-type rail pads can be obtained from the least-square optimization of the frequency response functions (FRFs) obtained from modal testing measurements.

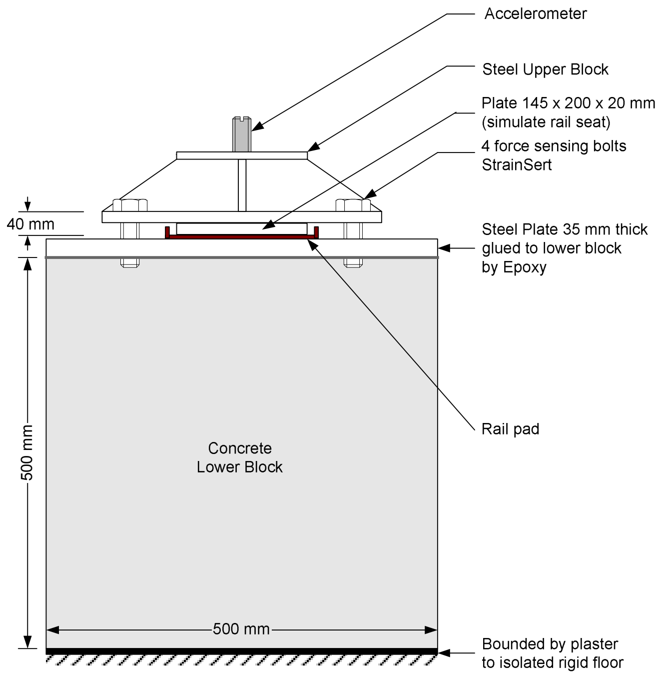


Figure 4. Schematic diagram of the innovative rail pad tester developed at UoW

2 THEORETICAL OVERVIEW

In this study, the rail pad is considered as the only elastic element in the test rig, as shown in Figure 4. This test rig has been developed using indirect measurement. 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 (Remennikov and Kaewunruen, 2005). The dynamic model of rail pads represents two main important parameters: dynamic stiffness and damping constant.

2.1 *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 Figures 2a. The dynamic characteristics of rail pads in the vertical direction can be described by the well-known equation of motion:

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

$$\omega_n^2 = {k_p}/{m}\ ,\quad 2\zeta\omega_n = {c_p}/{m}\ ,\ \text{or}\quad \zeta = {c_p}/{2\sqrt{k_p m}} \tag{2a, b, c}$$

where m_p, c_p, and k_p 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

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

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:

$$H(f) = \frac{1}{m_p}\frac{4\pi^2\beta f^2}{\sqrt{\left[1-4\pi^2\beta f^2\right]^2 + \left[4\pi^2\beta\left(\frac{c_p^2}{k_p m_p}\right)f^2\right]}} \tag{4}$$

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.

2.2 *Vibration Measurement*

To measure the vibration response of the rail pads, an accelerometer was placed on the top surface of the railhead, as illustrated in Figure 4. The mass of the upper segment is 30.30kg, and the mass of each preloading bolt is 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 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 0–3,500 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 rail system. The coherence function represents the quality of FRF measurements and should be close to unity.

2.3 *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 achieves these dynamic properties. 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. The dynamic properties can be obtained from the optimization. The correlation index (r^2) is the target function while each 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}. 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).

3 EXPERIMENTS

3.1 *Rail Pads*

All standard sizes of rail pads can be tested using this rail pad tester. Two types of unused rail pads are chosen (Figure 1), including high-density polyethylene (HDPE) and studded rubber pads. As supplied by the manufacturer (PANDROL), the dynamic stiffness of HDPE pads is ranging from 700 to 900 MN/m, while the dynamic stiffness of studded rubber pads is about 45-65 MN/m. Table 1 gives the general data of the pad specimens. These two specimens of rail pads are the available types, which are widely used in Australian railway networks for either passenger or heavy haul rolling stocks, i.e. Sydney Suburban Network, Queensland Rails' tracks, etc.

Table 1. General data of rail pad specimens.

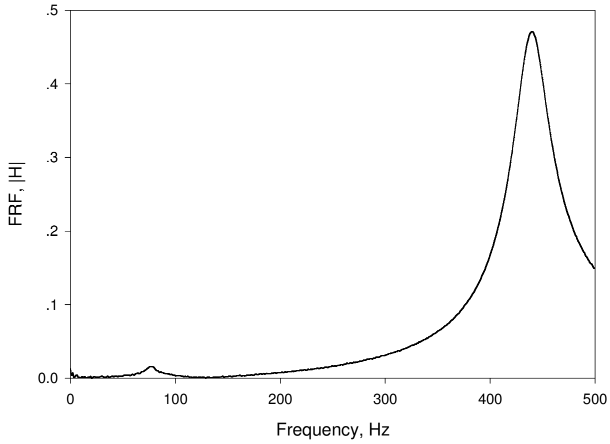
Type	Area	Thickness	Shape
	cm^2	Mm	
Studded rubber	267	10	Studded
HDPE	263	5.5	Plane

3.2 *Preload Control*

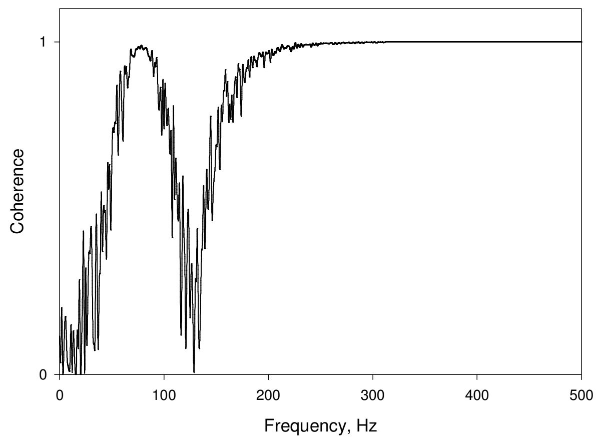
The test rig has been designed to apply preloads up to a maximum of approximately 400kN in total. Each calibrated force-sensing bolt is connected to real-time data logger and to computer. Using four force-sensing bolts (StranSert), the preloading can be read, adjusted and recorded through a computer screen. About 10 preloads on a real-scale rail pad from 0 to 200 kN are considered. Dynamic effect on rail pads under this large amount of preloading has never been investigated. It should be noted that the preload of 20 kN is equivalent to average preload of the PANDROL e-Clip fastening system on the rail. Also, the preload of 200kN is comparable to 40-ton axle load (Esveld, 2001).

3.3 *Modal Testing*

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, 10mm thick) were determined using the test rig and the results are presented in Figure 5. They included: the magnitude FRF (Figure 5a) and the coherence function (Figure 5b) that confirmed a high degree of linearity between input and output signals. Parameter optimization was then applied to the experimental FRFs, yielding the dynamic properties of rail pads under various conditions, see details in ref: Remennikov and Kaewunruen (2005).



a) FRF

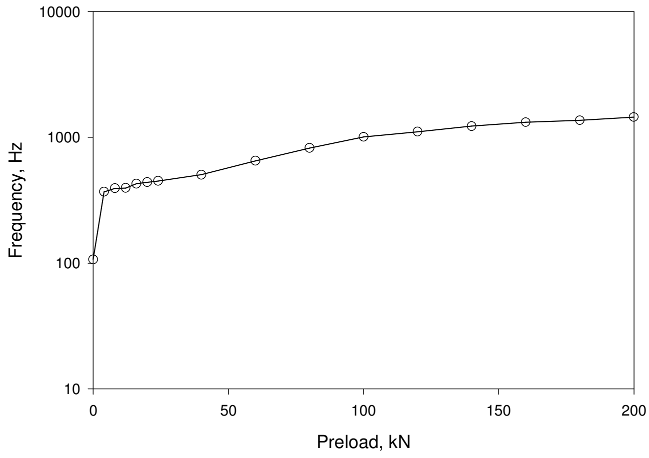


b) Coherence

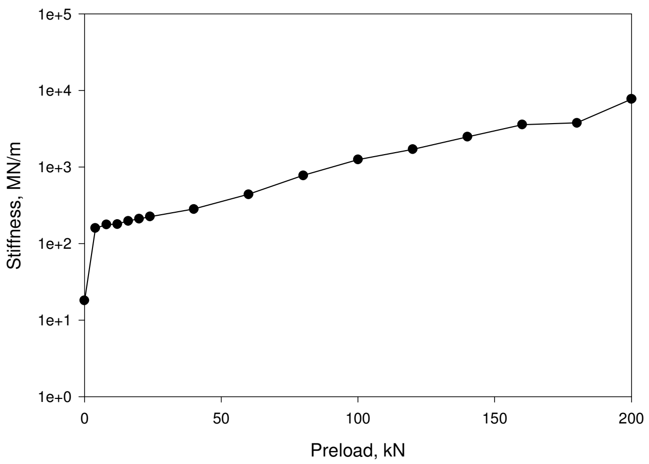
Figure 5. Frequency response function and its coherence of the tested studded rail pad under a preload of 20kN.

4 TEST RESULTS

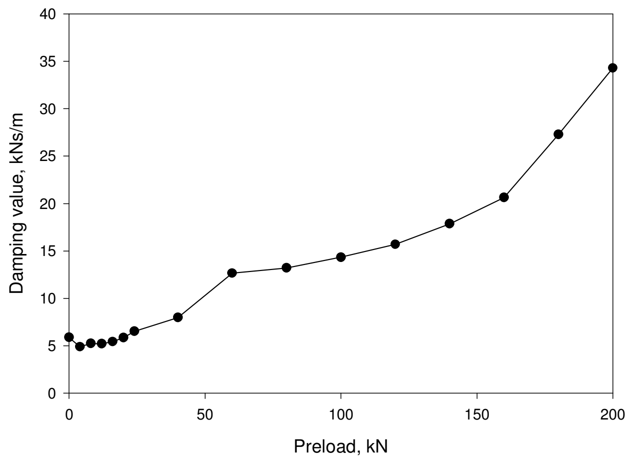
The resonance frequencies and corresponding dynamic properties of HDPE and rubber pads are presented in Figure 6 and 7. The results at preload of 20kN are comparable to the previous research results tested by the Track Testing Center (TTC) of Spoomet, South Africa, and by TU Delft (DUT) of the Netherlands (Van't Zand, 1993).



a) natural frequencies

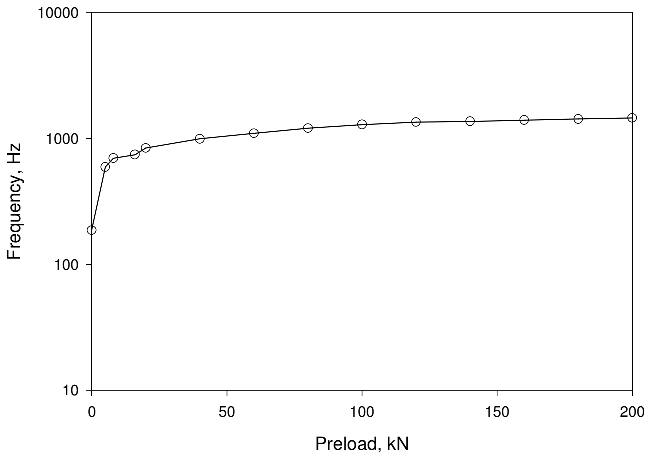


b) dynamic stiffness

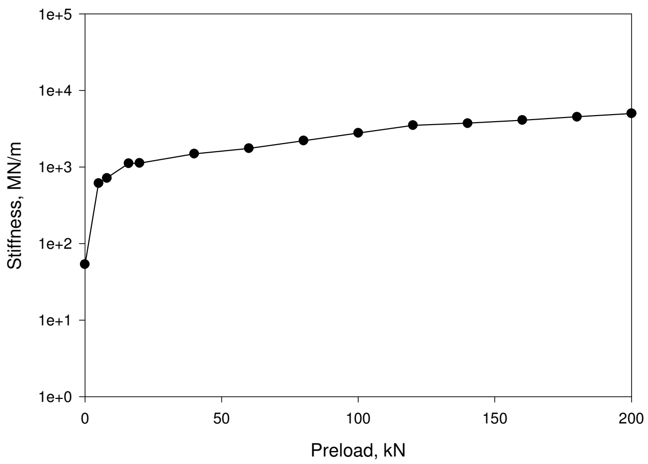


c) damping values

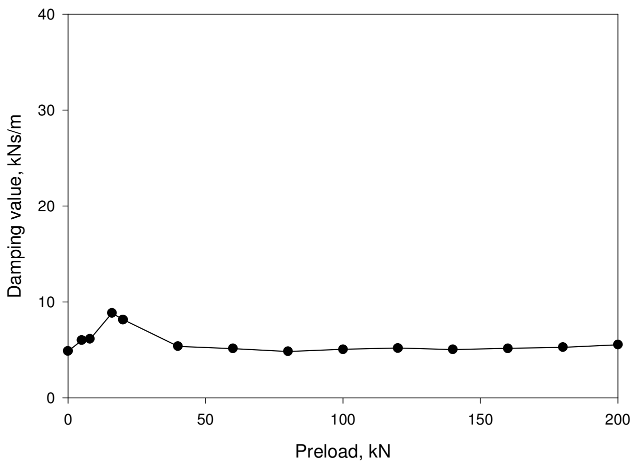
Figure 6. Natural frequencies and corresponding dynamic properties of the studded rail pad under large preloads.



a) natural frequencies



b) dynamic stiffness



c) damping values

Figure 7. Natural frequencies and corresponding dynamic properties of the HDPE rail pad under large preloads.

It is found from Figure 6a that, at low to moderate amount of preloads, the effect of preloading on resonance frequencies of studded pad is remarkable. This effect fades away when the preload is higher. As seen in Figures 6b and 6c, they show the clear tendency of substantial increases in both dynamic stiffness and damping values with incremental preloads.

On the other hand, Figure 7 evidently shows that only do very low preloads play a noticeable role on resonance frequencies and corresponding dynamic characteristics of HDPE pad. While at the moderate to high preloads, the preloading seems to have slight influence on dynamic stiffness but no impact on either resonance frequencies or damping coefficients.

Resonance frequencies of studded rubber pads tend to be less than HDPE pads at low to moderate preloads. However, at high preloads, the effect of preloading on the resonance frequencies seem to be significantly less, resulting in the close values of the natural frequencies. Although the studded pads have lower dynamic stiffness than HDPE pads at low amount of preloading, they are likely to gain benefit from high preloads and behave considerably stiffer. Interestingly, the damping mechanism of studded rubber pads is susceptible to incremental preloads, while in the HDPE pads damping mechanism needs a certain level of preload for driving full mechanism and is then invulnerable to any further preloads.

5 CONCLUSION

An alternative rail pad tester based on the SDOF vibration response measurement for determining the dynamic properties of rail pads subjected to incremental preloads was devised. Adopted is the impact excitation technique, which was demonstrated to be a simple, reliable, 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 all new types of rail pads as well as identification of the influences of incremental preloading on their dynamic characteristics. It was found that the preloads and level of preloading have remarkable influence on natural frequencies and corresponding dynamic properties of studded rubber pads. On the other hand, except for dynamic stiffness, HDPE pads seem not to have much relationship to preloading. It is evidently noted that the damping mechanism of studded rubber pads is significantly more susceptible to that of HDPE pads.

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