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NON-DESTRUCTIVE EVALUATION FOR DYNAMIC INTEGRITY OF RAILWAY TRACK STRUCTURE

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ABSTRACT

In-field testing for structural integrity using dynamic non-destructive investigation of ballasted railway track structures was carried out and is presented in this paper. A non-destructive technique, 'modal analysis', was utilised in this investigation. The railway track structures were dynamically excited using an impact excitation instrumented hammer. Due to the nature of railway track structures that they extrude for a long distance, the transient excitation was given randomly at several local areas. Acceleration responses in time domain were recorded using an accelerometer mounting on the railhead. The frequency response functions (FRFs) can be obtained via the PULSE FFT Analyser. The analytical formulation and best curve fitting algorithms were developed to identify the dynamic properties of railway tracks' components. Rather than providing only the absolute solutions, this paper points out more on how to judge the dynamic responses (e.g. FRFs) together with the visual inspection of existing conditions from the field experience. Examples of testing results representing the deficient integrity are additionally highlighted. Based on the results, the impact excitation technique is an efficient method susceptible to the structural integrity of railway track structures.

1 INTRODUCTION

Due to the heavy axles of coal trains in all regions throughout Australia, serious concerns associated with engineering conditions of track structures have arisen. Recently, there was a derailment of coal trains, costing millions of lost. This lesson greatly increases the concerns of track engineers to determine the conditions of rail tracks, especially in the potential risk zones. Apart from normal visual inspection by track officers, track corrugation tests are regularly performed at the track sites. The corrugation testing deals only with the individual rails and only railhead surface. In order to ascertain the systems conditions of railway tracks always subjected to train-induced vibrations, dynamic testing must be performed on tracks^[1-3] in which the dynamic properties can be extracted and estimated from the vibration responses of track structures. It should be noted that these parameters are important to dynamic analysis and design of structural systems, which are compliant to dynamic loadings, e.g. railway tracks, bridges, or high-rise buildings. The resonances can cause serious damages of such systems.

Nowadays, accelerating degradation of railway tracks creates many problems to railway engineers. Railway structures are degrading and deteriorating because of everyday services. Moreover, the irregularities of wheels, rails, or track properties remarkably influence the damages. Data on the structural integrity and deterioration of railway tracks is very limited. Structural conditions of railway tracks are typically not known either before or after maintenance procedures. Thereby, in practice the maintenance and renewal operations are usually based on empirical criteria. It has been found that better understanding of the structural conditions and the deterioration rates could lead to the improved

strategic planning and implementation of railway tracks^[4]. To maximize safety while minimizing costs of track maintenance and renewal, evaluation and monitoring of the structural integrity of railway tracks and its components are compulsory.

A number of testing approaches is available to undertake the evaluation and monitoring of the dynamic integrity of track structures^[5]. It is found that a most practical one is to use an instrumented impact hammer to impart excitations into the in-situ/in-field tracks and to use an accelerometer for measuring the dynamic responses^[6, 7]. This analogy has been successfully extended to the railway track structures in an urban environment^[8, 9]. In these studies, a two-degree-of-freedom (2DOF) dynamic model was used to simplify the railway track as a discretely supported continuous rail system. It consisted of two effective masses of rail and sleeper, two dynamic stiffness values, and two dashpots of rail pad and ballast formation, respectively. Experimental modal analysis has been found to be a very useful tool in evaluating the properties of railway tracks. Kaewunruen and Remennikov^[10, 11] has developed a finite element simulation and a 2DOF approach for the condition assessment of railway tracks, with the validations to field trial data. The results showed that 2DOF model is sufficient to represent the major track behaviours: in-phase and out-of-phase resonances. They have proven that modal testing is very suitable for the field investigations to evaluate the structural integrity of the railway tracks.

In Australia, based on the critical demand of importing coal in Asia and Europe, many railway industries operate the coal lines to ports for more than 10 stocks every day, significantly causing track irregularities and deterioration. The structural integrity of current track

components has been under suspicion for resisting current intensive mission, resulting in the requirement of a non-destructive evaluation of structural integrity of railway tracks. As part of Rail CRC project, the University of Wollongong (UoW) joined forces with Queensland Rail (QR) and Queensland University of Technology (QUT) to comprehensively investigate a selected heavy haul railway network in Central Queensland, Australia, see Figure 1.

Experimental modal testing is utilized in these field investigations since this methodology is a very effective, mobile, and non-destructive testing^[12]. Based on the discrete support model, equations of motion of a 2DOF dynamic model of railway track has been formulated using fast fourier transform (FFT) approximation technique, in order to extract the modal properties of track components from the field dynamic testing results obtained using an instrumented hammer impact technique. However, the dynamic responses obtained imply the local track behaviours only. Thus, random positions to be tested must be of a wide range that could represent the integrity of whole area.

This paper presents a non-destructive testing approach that combines field testing and experimental modal analysis to evaluate the dynamic integrity in terms of parameters of in-situ railway track components. At present, only ballasted railway tracks are considered. Some sleeper-fastening-rail assemblies were chosen for examples that show different level of dynamic integrity of the tracks. The frequency response functions (FRFs) were recorded by using Bruel & Kjaer PULSE vibration analyser in a frequency domain between 0 and 1,600 Hz. The frequency of interest was up to 600 Hz^[11]. The data obtained were optimised using best curve fitting technique to estimate the dynamic stiffness and damping constants of the tested track components. These results can supply a track engineer on the current structural conditions of the railway track. The experimental natural vibrations together with the dynamic properties of each track component can provide a significant input for determining the maximum speed and axle load for the future track upgrades.



Figure 1. Typical ballasted railway track in Australia

2 VISUAL INSPECTION

Referring to Figure 1, the ballasted track system is thoroughly used in this region. At the test sites, visual inspection for observable defects and faults was carried out. Overall conditions of rail track structures were found in good statuses of both superstructure and substructure. There are not many irregularities found on the railhead surface, such as dip-joints, squats, wheel burns, wears, and so on. However, in few places, damage of rail fastening system, cracks in concrete sleepers, and so on, incurred as depicted in Figure 2. Figure 2a) shows the cracks in the mid span of sleepers, Figure 2b) shows the coal-ballast mixture and Figure 2c) is the short-pitch corrugation on rails.

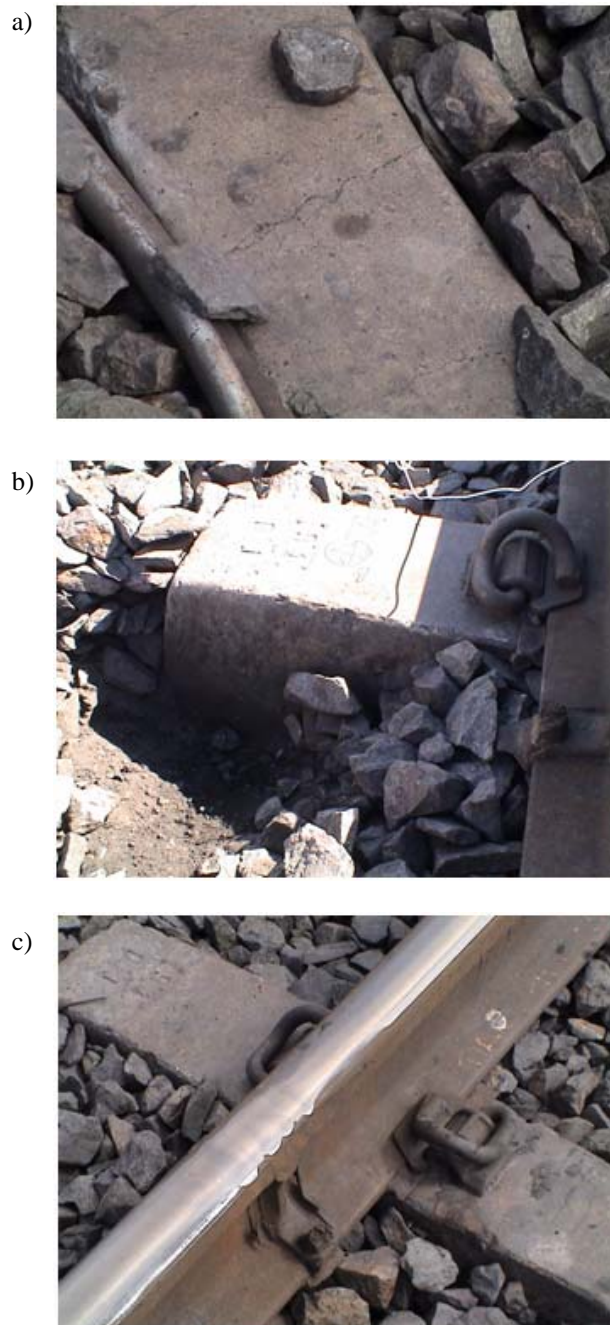


Figure 2. Visual inspection

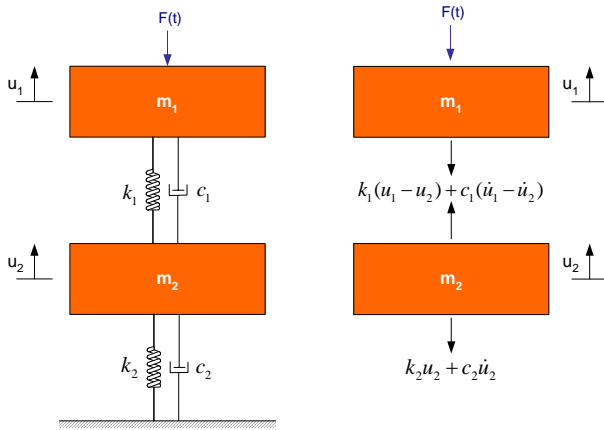


Figure 3. 2DOF dynamic model (after [11]).



Figure 4. Dynamic testing installation

3 NON-DESTRUCTIVE TESTS

Experimental modal analysis (EMA) or so-called *modal testing* is a non-destructive testing strategy based on vibration responses of the structures. In-situ and in-field dynamic testings on global ballasted track have been done mostly based on the instrumented hammer impact technique. This is because the impact hammer owns many advantages; for example, it is mobile and self-supporting^[6, 7]. Also, it can be used without damage or obstruction to traffic^[12]. The integration of analytical models and experimental results has led to integrity assessments of the rail track structures.

As a result, the experimental modal analysis is used in this study as a non-destructive testing technique^[13]. Modal data in terms of frequency response functions (FRFs) obtained from field measurements can be used to predict the dynamic and resonant behaviors of in-situ tracks in the real condition, as well as the dynamic parameters of those structures, such as natural frequency, dynamic stiffness, damping constant, corresponding mode shape. Major outcomes of the in-field testing are to assess the structural health conditions of rail assemblages, i.e. concrete sleepers, rail bearing pads, and supporting ballast/formation. These result in the evaluation of the integrity of current tracks and their optimal track maintenance and renewal, and also lead to the development for a database of the modal data for monitoring the structural health and degradation of the railway track. In addition to condition assessments, a reason of the dynamic test is that those outcomes allow verifying a dedicated numerical model of the track system. The analytical model, which has been validated, can be used in design and response prediction with confidence. The structural modifications in computer simulations could yield further sensitivity analysis and the design of speed and axle loads for the future upgrading of railway track.

The field measurements were carried out in March 2005 on an existing track of a coal line in Central Queensland, Australia. The track has been constructed for heavy haul purposes since 1991. The line provides the transport to coal mines, serving the 2-kilometre long heavy-haul coal trains passing by every 20 minutes^[10]. The in-field testing was carried out by means of instrumented hammer impact technique. Both a small instrumented hammer (300g mass) and a large sledge hammer (5kg mass) were employed to evaluate the dynamic properties of the railway track. As mentioned, this study is based on the fact that the railway track can be simplified as a 2DOF discretely supported continuous rail as shown in Figure 3.

The hammers were used to hit at railhead to impart excitation to the track system. An accelerometer was installed on the railhead as illustrated in Figure 4. Both the impact hammer and accelerometer were connected to the Bruel & Kaejar FFT PULSE System through which the frequency response functions (FRFs) could be captured. In order to extract the dynamic properties of the ballasted track systems, the analytical models of the 2DOF model depicted in Figure 3 have been developed based on the Fast Fourier Transform (FFT) method. The developed analytical expression is established in Equation (1)^[10, 11]. Note the notations in Equation (1) that, m_1 and m_2 are masses of rail and sleeper, k_1 and c_1 represent stiffness and damping coefficients of the rail, and k_2 and c_2 represent stiffness and damping coefficients of ballast supporting system. It should also be noted that system parameters in Equation (1) represent the actual stiffness, actual damping value, and actual mass. This equation is to be used in least square optimisation^[14] for the identification of the dynamic system parameters.

$$H_{11}(f) = \frac{\sqrt{[k_1 + k_2 - 4\pi^2 f^2]^2 + [2\pi f (c_1 + c_2)]^2}}{\sqrt{[(k_1 - 4m_1\pi^2 f^2)(k_2 - 4m_2\pi^2 f^2) - 4\pi^2 f^2 (k_1 m_1 + c_1 c_2)]^2 + 4\pi^2 f^2 [k_1 c_2 + k_2 c_1 - (m_1 (c_1 + c_2) + c_1 m_2) 4\pi^2 f^2]^2}} \quad (1)$$

4 FIELD TRIAL MEASUREMENTS

In this paper, the experimental data are exemplified aiming at enhancing the insight into the non-destructive testing and its interpretation. Three samples of field data, including the good condition areas, broken fastening system site, and a track with cracked sleeper, are illustrated as follows.

4.1 Good condition tracks

Figure 5 present the FRF and coherence functions of the non-destructive tests generally found in the good condition railway tracks. FRF represents the dynamic responses of local system to given excitation, while the coherence provides the quality level of the response signals. Based on the visual inspection, the track was in good conditions. The rail gauge was normal in general. The sleeper and ballast supporting system were in good conditions. In the frequency range of interest, the quality of the response is very high.

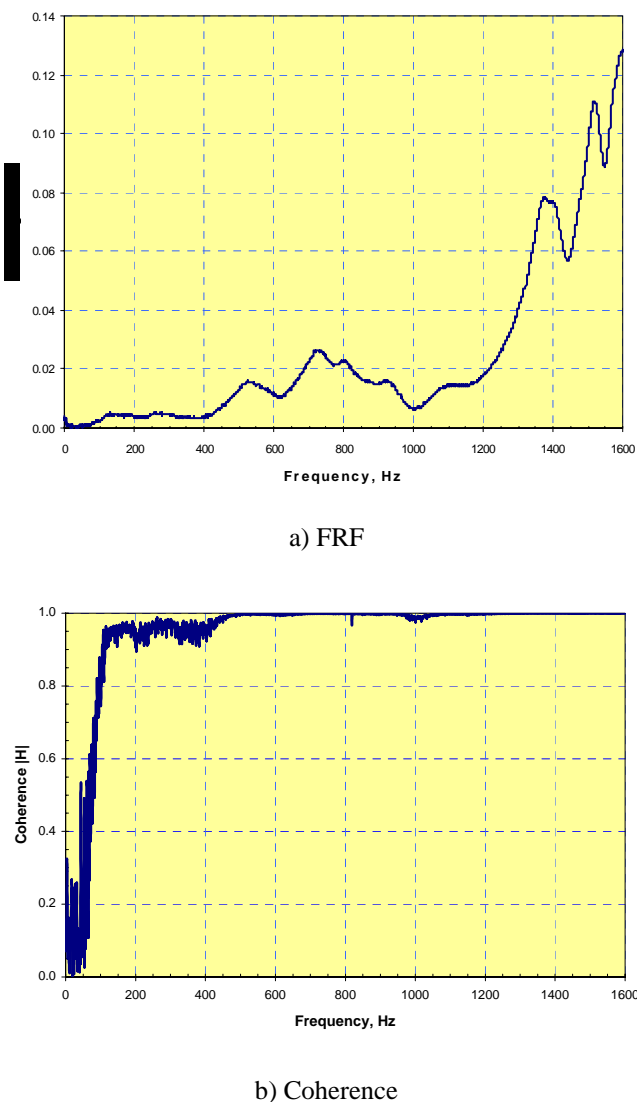


Figure 5. Measurements on a good condition site

4.2 Loosening rail fastening system

From visual inspection, at a glance it was unable to notice that the rail fastening system was broken. The modal testing was performed. The frequency response functions (FRFs) were recorded on the site, as shown in Figure 6a. The coherence function that associates with quality of signals is also shown below in Figure 6b. From the FRF, it can be read clearly in the frequency range of interest (up to 600 Hz) that there must be a defect in that local track system. The search on track was carefully performed. It was found that the rail fastening system (e-Clip) was broken and did not hold the rail gauge to the concrete sleeper.

4.3 Cracked sleeper

As illustrated in Figure 2a, the track with cracked sleeper at mid span was tested. Figure 7 illustrate the dynamic responses by means of FRF and coherence functions. It is found in the FRF that many peaks occur between the first and second peak.

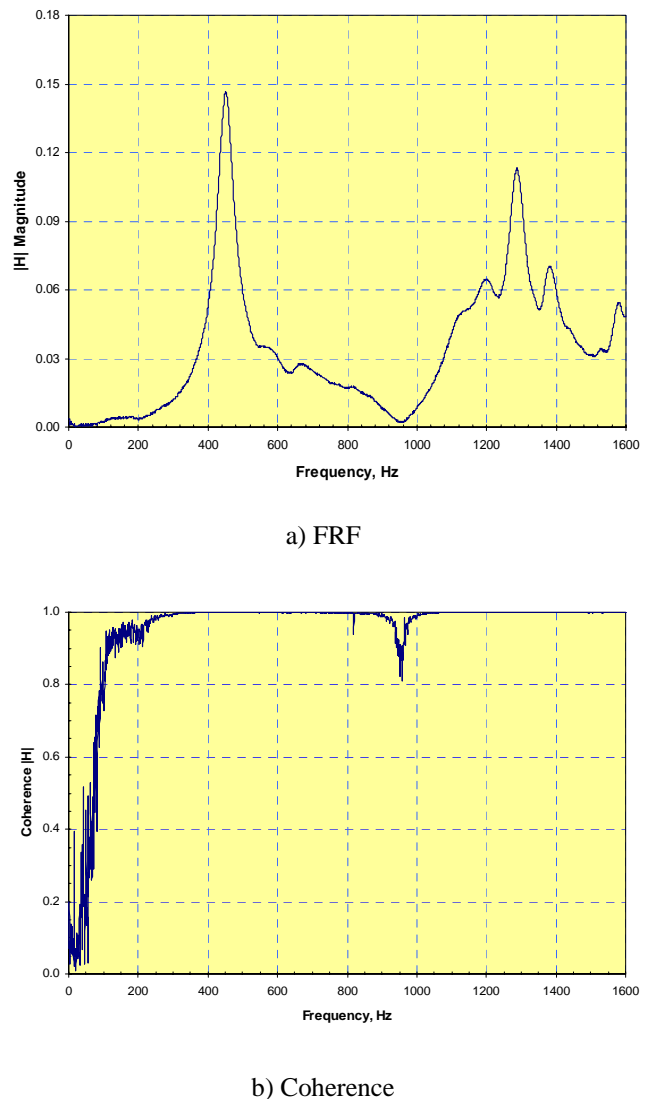
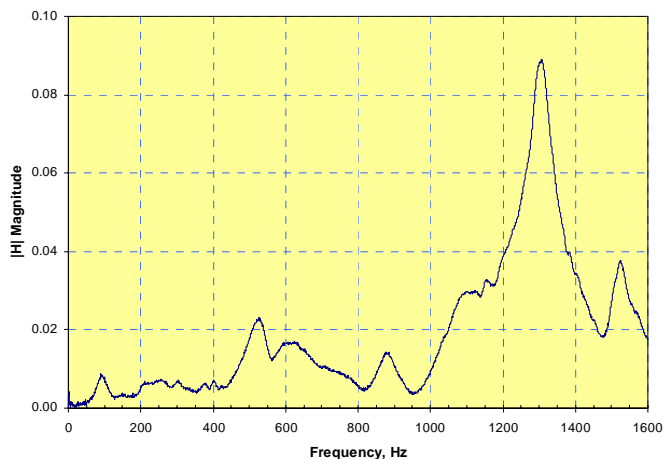
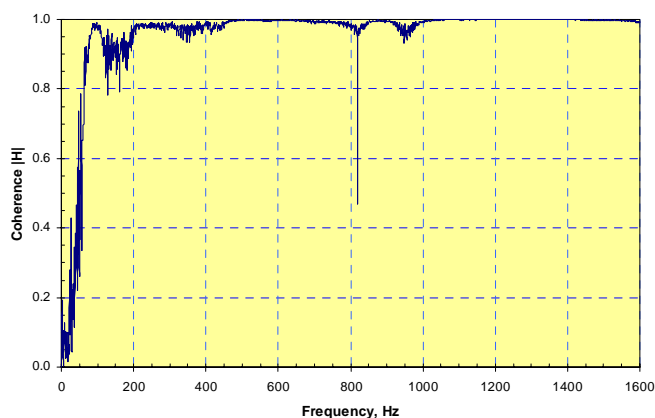


Figure 6. Measurements on a site with broken e-Clip



a) FRF



b) Coherence

Figure 7. Measurements on a site with cracked sleeper

5. INTEGRITY EVALUATION

The field data obtained from the non-destructive tests were processed using the FFT approach. The curve fitting algorithms were developed on the basis of least square optimization technique, using a curve-fitting package DataFit^[14]. The objective equation is based on Equation (1). The FRFs obtained were tuned for the dynamic parameters. An example of the curve-fitting results is presented in Figure 8.

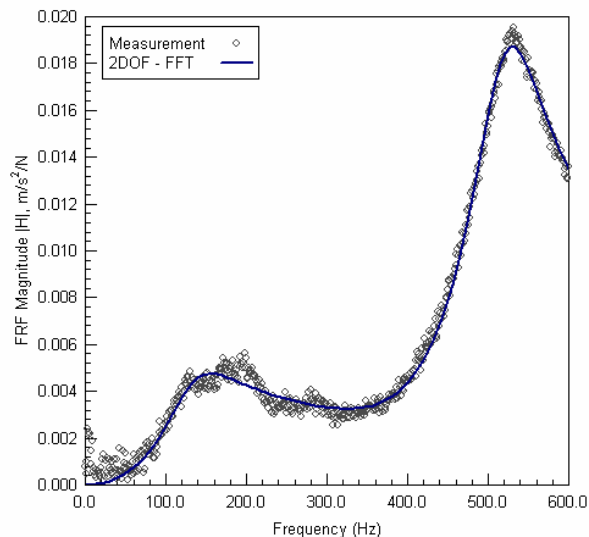


Figure 8. Best curve fitting of FRF in Figure 5a

Dynamic properties that reflect the dynamic integrity of the railway track can be predicted from the curve fitting and tabulated in Table 1.

In general, the good condition railway tracks would provide the dynamic responses in the frequency range of interest (0-600 Hz) to impact excitation in a very good agreement with theoretical simulations as portrayed in Figure 5a. Railway tracks would behave like a 2DOF dynamic model as it could be seen that the FRFs consist of two apparent resonance peaks (see Figure 8). In addition, the coherence function is presenting that good signals were obtained. It should be noted that the first peak is the natural vibration of substructure (e.g. sleeper on ballast/subgrade) and the second peak is the vibration of superstructure (e.g. rail on rail pad). After curve fitting, the dynamic properties of the railway track were found close to other previous works^[11].

The FRF of the track with loosening rail fastening system looks similar to those found in a SDOF dynamic model, see Figure 6a. There is only one dominant peak during the frequency range of interest and very clear signal as seen from its coherence in Figure 6b. The dynamic responses of substructure in low frequency diminished since there is no connection between

Table 1. Dynamic properties of railway tracks

Site (0-600Hz.)	Correlation r^2	Superstructure (Upper Part)		
		C_{pad} (Ns/m)	K_{pad} (N/m)	M_{rail} (kg)
A	0.993433	1,339.77	963,410,355.7	168.9247
B	0.994230	19,080.67	590,764,209.4	74.6282
C	0.885344	5,000	564,983,227.6	125.7710
Site	Correlation r^2	Substructure (Lower Part)		
		C_{ballast} (Ns/m)	K_{ballast} (N/m)	M_{sleeper} (kg)
A	0.993433	254,295.62	282,214,086.0	204.4043
B	0.994230	0	0	0
C	0.885344	97,921.15	50,276,789.9	94.7183

Note: A: Good condition track (Figure 5)
 B: Track with broken rail fastening system (Figure 6)
 C: Track with cracked sleeper (Figure 7)

superstructure and substructure. Clearly, Table 1 shows the curve fitting results in which poor integrity of substructure is eminent. Noteworthy, this is the sign of defect on fastening system that track engineers should be aware of.

In case of the track with cracked sleeper, the FRF signal presents not much information for judgement on any observable defects. However, it can be noticed from the FRF in the frequency range between 0 and 600 Hz that there are a number of small but strong peaks arisen. This would result in a difficulty in best curve fitting processes. From curve fitting results, it can be found that the cracked sleeper significantly reduces the dynamic mass and stiffness of substructure, whilst cracking remarkably increases the damping of system, in terms of increased friction in concrete material.

6. CONCLUSION

The degradation of railway track can cause serious problems. This raises a concern on integrity evaluation of railway track at current state. The in-field dynamic testing in combination with track simplification represents an efficient and non-destructive strategy for identification of the current condition of railway track structure and its components.

In this paper, the non-destructive testing technique employed was experimental modal analysis. Modal results were obtained from the field measurements and used to assess the current state of the railway track. For practical purposes, this paper integrates field measurements, experimental modal analysis and track simplification to evaluate the dynamic integrity of in-situ railway track structure. The railway track is simplified as a two-degree-of-freedom (2DOF) dynamic system. Optimization technique and algorithm for track model has been developed in order to extract the dynamic properties of track components from the field measurements using instrumented hammer impact technique. A railway track site in Central Queensland, Australia, has been selected to perform the field tests. The frequency response functions (FRFs) have been recorded by using Bruel & Kjaer PULSE vibration analyser in a frequency domain between 0 and 1,600 Hz. However, it is found that only from 0 to 600 Hz is ample for the optimisation of the signals. The data collected in that frequency range have been tuned using least-square curve fitting to determine the dynamic stiffness and damping constants of the tested track components.

The advances of this paper are the non-destructive testing technique and criteria to evaluate the integrity of track structure. These could supply railway industry for the evaluation on the current state and also for health monitoring of the railway tracks. Three samples that include major defects found in general track problems, e.g. loosening e-Clip and cracked sleeper, are clearly illustrated. In addition, the experimentally determined resonance frequencies along with the dynamic properties of the track components are presented to

provide new practitioners as the guidance and for an initial input in the dynamic analysis of railway track package for determining the maximum speed and axle load for the future track upgrades or functional changes.

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