Integrated field measurements and track simulations for condition assessment of railway track

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INTEGRATED FIELD MEASUREMENTS AND TRACK SIMULATIONS FOR CONDITION ASSESSMENT OF RAILWAY TRACK

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Abstract

Assessment of condition of railway track is crucial for track design, repair and effective maintenance operations. In-field dynamic testing in combination with track modelling represents an efficient strategy for identification of the current condition of railway track structure and its components. This paper presents an integrated approach combining field measurements, experimental modal analysis and finite element modelling to evaluate the dynamic parameters of the in-situ railway track components. Based on the discrete support model, a two-degree-of-freedom (2DOF) dynamic model of railway track is analysed in order to extract the modal properties of the track components from the field dynamic testing results obtained using an instrumented hammer impact technique. A railway track site in Central Queensland managed by Queensland Rail (QR) was selected to perform the field tests. Five sleeper-fastening-rail assemblies were selected for dynamic testing. 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 data obtained have been best fitted using the least-square technique to determine the dynamic stiffness and damping constants of the tested track components. These results can supply a track maintenance engineer with very important information on the current state of the railway track. In addition, the experimentally determined resonance frequencies along with the dynamic properties of the track components can provide an important input for determining the maximum speed and axle load for the future track upgrades.
Keywords: Railway track, condition assessment, field measurement, track simulation, dynamic testing, vibration characteristics.

1. Introduction
Demand for mass transportation, freight, and coal transport across a continent has become a major contribution driving research and development in railway industry to build railway tracks meeting such variety of services. Everyday there exist increasingly the needs of railway utilization (e.g. heavier axle loads, faster speeds, more frequent, etc) whilst the existing track infrastructure is questioned for its current capacity, functionality, and remaining service life. As well known, the railway structures are inevitably degrading and deteriorating due to the everyday services. Information on the structural integrity and deterioration of railway tracks is very limited. The relationships between deterioration and maintenance/renewal associated with railway infrastructure would be of great interest to track engineers and managers concerned with minimising maintenance/renewal costs. Having better understanding of maintenance and renewal and the deterioration rates could lead to the improved strategic planning and implementation [1]. In reality, structural conditions of railway tracks are typically not known either before or after maintenance procedures since in practice the maintenance and renewal operations are usually based on empirical criteria.

At present, accelerating degradation of railway tracks creates many problems to railway engineers. In order to both maximize safety and minimize costs of track maintenance and renewal, assessment and monitoring of the structural health of railway track and its components must be done. There are a number of testing methodologies available to undertake the identification and monitoring of the conditions of the track structures [2]. However, one of the most practical approaches is to use an instrumented impact hammer to impart excitations into the in-situ/in-field tracks and to measure the dynamic responses for condition assessment [3, 4]. This method has been successfully extended to the track structures in an urban environment [5, 6]. In those studies, the track was simplified as a two-degree-of-freedom (2DOF) discretely supported continuous rail system representing two effective masses of rail and sleeper, as well as two dynamic stiffness and two dashpots of rail pad and ballast-formation, respectively. Modal testing has been found to be a very useful tool in assessing the properties of railway tracks. In this study, modal testing was adopted for the field investigations while the analytical and FEM models were used to evaluate the structural conditions of the railway tracks.

In Queensland, Australia, there are various problems identified on the coal lines due to the heavy axle loads and tilt topography. The structural integrity of the track components on some of the lines needed to be investigated. As part of the Rail-CRC project, the University of Wollongong (UoW) together with Queensland Rail (QR) and Queensland University of Technology (QUT) joined forces to investigate the conditions of a heavy haul railway track in Mackay, Central Queensland [7], as illustrated in Figure 1. Modal results were obtained from field measurements and used to assess the current structural conditions of the railway track.
This paper presents an integrated approach that combines field testing, experimental modal analysis and finite element modelling to evaluate the dynamic parameters of in-situ railway track components. Based on the discrete support model, a 2DOF dynamic model of railway track is developed in order to extract the modal properties of track components from the field dynamic testing results obtained using an instrumented hammer impact technique. Six sleeper-fastening rail assemblies were selected for dynamic testing. 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 data obtained were processed using least-square curve fitting technique to determine the dynamic stiffness and damping constants of the tested track components. These results can supply a track maintenance engineer with very important information on the current structural conditions of the railway track. In addition, the experimentally determined resonance frequencies 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. However, in this study only ballasted railway tracks are considered.
2. Track simulations

One of the first analytical models of railway track dynamics was developed by Timoshenko in 1926 [8]. In that model, the rail was considered as an infinite uniform Euler beam, laid on a continuous damped elastic Winkler foundation. Later, Grassie and Cox [9] found from the experiments that there are only two dominant resonances in the frequency range of interest for railway track. The first resonance, an in-phase mode at about 100 Hz, corresponds to the sleeper and rail moving together on the ballast. The second resonance, the out-of-phase mode at the frequency somewhere between 300-500 Hz depending on the rail pad parameters, corresponds to the opposite vibration of sleepers on ballast and rails on the railpad. Cai [10] found that modelling the rail and sleeper as Timoshenko beam provides the best analytical results.

![Diagram of a typical ballasted track](image)

**Figure 2** Typical ballasted tracks

For design and maintenance purposes, complicated models of railway tracks seem to be impractical when considering the field testing [2]. It has been demonstrated that simple analytical and finite element models calibrated using experimental data are capable of providing reliable predictions of railway track vibration response. In this study, the ballasted tracks are considered as shown in Figure 2. The Grassie's model [11] based on discrete sleeper support model has been employed for track simulations. The results of the finite element model of railway track show that there are three dominant resonances, which are in a very good agreement with previous findings [11, 12]. The dominating resonance frequencies represent the in-phase, out-of-phase, and pin-pin vibration modes of railway track. As shown in Table 1, the in-phase and out-of-phase modes can also be predicted using a simple 2DOF mass-spring system. As a result, the 2DOF mass-spring models have been widely used to identify the in-field dynamic conditions of railway tracks using the impact excitation techniques [7, 12].
### Table 1: Dynamic behaviour of simplified railway tracks

<table>
<thead>
<tr>
<th>Finite element model</th>
<th>2DOF mass-spring system</th>
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<tbody>
<tr>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
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<tr>
<td>rail</td>
<td>rail</td>
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<tr>
<td>ballast supporting</td>
<td>sleeper</td>
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<td>system</td>
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</tbody>
</table>

#### 3. Field dynamic measurements

The field measurements were carried out in March 2005 on the existing track of a coal line between Nebo and Hay Point Port in Mackay, Central Queensland, Australia. The track has been in service since 1991. The line provides services to the coal mines at Goonyella utilising the 2-kilometre long heavy-haul coal trains passing by every 20 minutes [7].

The in-field testing was carried out by means of excitation hammer testing. A small instrumented hammer and a large sledge hammer were used to evaluate the dynamic properties of a railway track. In this test, the track was simplified as a 2DOF discretely supported continuous rail as shown in Figure 3. The hammer was used to hit railhead to impart excitation to the track system. An accelerometer was mounted on the railhead as illustrated in Figure 4. Both the impact hammer and accelerometer were connected to the B&K FFT PULSE acquisition system through which the frequency response functions (FRFs) could be measured.
Figure 3: 2DOF dynamic models of railway track

Figure 4: Dynamic testing installation
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) and Mode Superposition (MS) methods. The developed analytical expressions are given in Equations (1) and (2) for FFT and MS methods, respectively [7]. In these equations, $m_1$ 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 be noted that system parameters in Equation (1) represent the actual stiffness, actual damping value, and actual mass. In contrast, Equations (2) are formulated in terms of modal stiffness, modal damping, and modal mass based on MS method. These equations are to be used in least square optimisation for the estimation of the dynamic system parameters.