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Non-destructive testing (NDT): A tool for dynamic health monitoring of railway track structures

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NDT: a tool for health monitoring of railway track structures

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The applications of NDT are varied and recently, an NDT technique known as 'modal analysis' was adopted in railway engineering in order to measure track behaviours under either train services or man-made loadings.

OVER THE PAST decade, modal testing has become an effective means for identifying, understanding, and simulating dynamic behaviour and responses of structures. One of the techniques widely used in modal analysis is based on an instrumented hammer impact excitation. By using signal analysis, the vibration response of the structures to the impact excitation is measured and transformed into frequency response functions (FRFs) using the Fast Fourier Transformation (FFT) technique. Subsequently, the series of FRFs are used to extract modal parameters such as frequency, damping, and corresponding mode shape. In a range of practical applications the modal parameters are required to avoid resonance in structures affected by external periodic dynamic loads. Practical applications of modal analysis span over various fields of science, engineering and technology.

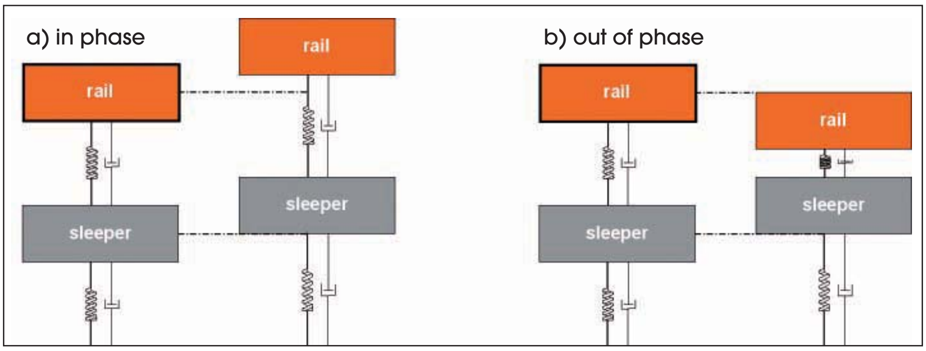

Figure 2: Simplification of railway track dynamics: a) in phase; b) out of phase.

Why do we need to monitor track health?

Due to the heavy axles of coal trains in all regions throughout Australia, serious concerns associated with engineering conditions of track structures have arisen. The rationale is that a train derailment costs millions of dollars in terms of life and asset. It 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 track sites, as shown in Figure 1. The corrugation testing deals only with the individual rails and only superficial railhead surface. In order to ascertain the condition of railway tracks always subjected to train-induced vibrations, dynamic testing must be performed on tracks 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, such as railway tracks, bridges, or high-rise buildings. The resonances can cause serious damages to such systems.

Figure 1: Corrugation tests in a typical ballasted railway track in Central QLD.

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. There is a need for better understanding into the structural conditions and the deterioration rates, which can lead to the improved strategic planning and implementation of railway tracks. To maximise safety while minimising costs of track maintenance and renewal, evaluation and monitoring of the structural integrity of railway tracks and its components is imperative.

Condition of Australian railway tracks

Based on demand in Asia and Europe to import coal from Australia, many railway industries operate coal lines to several ports for roughly 50,000 tonnes per day. This significantly causes track irregularities and deterioration. The structural integrity of current track components has been under suspicion for resisting current intensive mission, resulting in the need for non-destructive evaluation of the structural integrity of railway tracks. As part of a Rail-CRC project, the University of Wollongong (UoW) joined forces with Queensland Rail (QR) and Queensland University of Technology (QUT) to comprehensively investigate a heavy haul network in central Queensland. The experimental modal testing is used in these investigations as it is a very effective and mobile method of non-destructive testing.

The field measurements were carried out in March 2005 on an existing track of a coal line in central Queensland. The track has been used for heavy haul purposes since

Figure 3: Idealisation of 2DOF system.

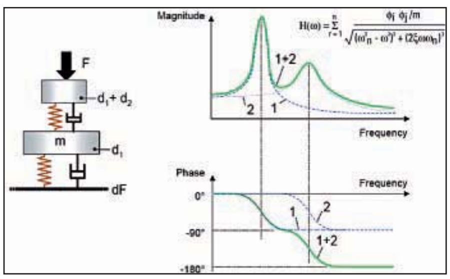

Figure 4: Dr Alex Remennikov performing the NDT test on a railway track.

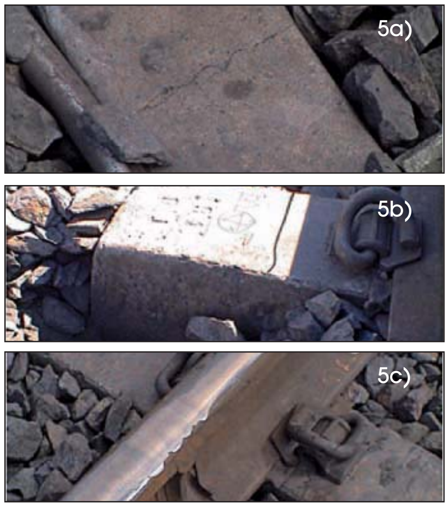

Figure 5: Visual inspection: 5a) cracked sleeper; 5b) combination of ballast and coal; 5c) rail corrugation.

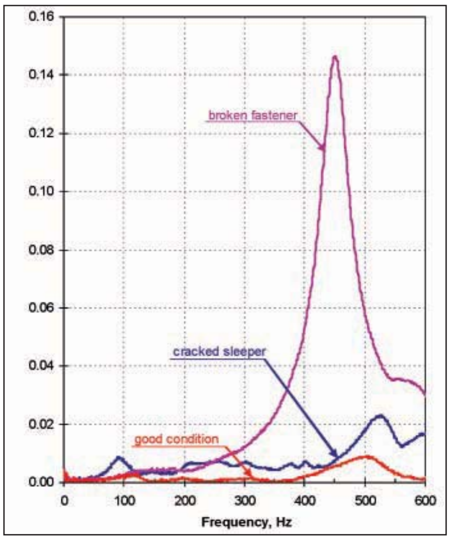

Figure 6: Frequency response function (FRF) of railway track structures.

1991. The line provides transport to coal mines, serving the 2 km heavy-haul coal trains passing by every 20 minutes. The in-field testing was carried out by means of instrumented hammer impact technique. Both a small instrumented hammer (300 g mass) and a large sledge hammer (5 kg mass) were used to evaluate the dynamic properties of the railway track.

The physics of railway tracks

A number of testing approaches are available for the evaluation and monitoring of the dynamic integrity of building structures using wave signals. It has been found that the most practical strategy for railway track structures is to use an instrumented impact hammer to impart excitations into the in-situ tracks and to mount accelerometers for measuring the dynamic responses.[1,2] This analogy has been extended to railway track structures in an urban environment.[3] To explain this, a two-degree-of-freedom (2DOF) dynamic system 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. Kaewunruen and Remennikov[4,5] have developed an integrated method using finite element simulation and a 2DOF approach for the condition assessment of railway tracks, as illustrated in Figure 2. The results showed the 2DOF model is sufficient to represent the major track behaviours: in-phase and out-of-phase resonances. The in-phase vibration behaves similar to the first mode of the 2DOF system where the rail and ballast vibrate in one direction. On the other hand, the out-of-phase resonance prevails when the rail vibrates inversely with the ballast which the second mode of the 2DOF system is similar to.

How does it work?

The NDT approach that combines field testing and experimental modal analysis can evaluate the dynamic integrity in terms of parameters of in-situ railway track components. Based on the discrete support model as shown in Figure 3, equations of motion of a 2DOF dynamic model of railway track have been formulated using the 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. 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 though which the frequency response functions (FRFs) could be captured. 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 an entire area. At present, only ballasted railway tracks are considered. Some sleeper-fastening-rail assemblies were chosen for examples that show different levels of dynamic integrity of the tracks. The FRFs were recorded by using a Bruel & Kjaer PULSE vibration analyser in a frequency domain between 0 and 1,600 Hz. The frequency of interest was up to 600 Hz.[4,6] The data obtained was optimised using the best curve fitting technique to estimate the dynamic stiffness and damping constants of the tested track components.

The ballasted track system is thoroughly used in central Queensland. At random test sites, visual inspection for observable defects and faults was carried out. Overall conditions of rail track structures were found to be good in terms 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 a few places, damage of rail fastening system, cracks in concrete sleepers, short-pitch corrugations and so on occurred, examples of which are depicted in Figure 5. Figure 5a shows the cracks on the mid span of sleepers, figure 5b shows the coal-ballast mixture and figure 5c shows the short-pitch corrugation on rails.

In this investigation, the experimental data is exemplified to enhance the insight into the non-destructive testing and its interpretation. Three samples of field data, showing areas in good condition, a broken fastening system site, and a track with a cracked sleeper are demonstrated in figure 6. The FRF of railway tracks generally found in the good condition railway tracks looks similar to the ideal responses in figure 4. In the frequency range of interest, the quality of the response was very high. Fastener

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damage was unnoticeable from visual inspection. After performing NDT, the FRF clearly shows that there is an irregularity of the signal. The search on track was carefully performed and it was found that the rail fastening system (e-Clip) was broken and did not hold the rail gauge to the concrete sleeper. When the track with a cracked sleeper at mid span was tested it was discovered that many peaks occurred between the first and second peak of the FRF signal.

Interpreting the signals

The field data obtained from the NDTs were processed using the FFT approach. The curve fitting algorithms were developed on the basis of least square optimisation technique, using a curve-fitting package DataFit.[7] The FRFs obtained were tuned for the dynamic parameters. Dynamic properties that reflect the dynamic integrity of the railway track can be predicted from the curve fitting. In general, the good condition railway tracks would provide the dynamic responses in the frequency range of interest to impact excitation in a very good agreement with theoretical simulations (Figure 6). It should be noted that the first peak is the natural vibration of the substructure (e.g. sleeper on ballast/subgrade) and the second peak is the vibration of the superstructure (e.g. rail on rail pad). The lowest FRF level represents the highest strength of the track system. After curve fitting, the dynamic properties of the railway track were found close to other previous works.[4,5] The stiffness in well conditioned tracks ranges from 800-1500 MN/m and 150-450 MN/m for rail pad and ballast, while the damping coefficients should be 1-60 kNs/m and 100-300 kNs/m respectively.

The FRF of the track with damaged fastening system looks similar to those found in a SDOF dynamic model. There is only one dominant peak and the response level is the highest as the rail can vibrate freely. Clearly, the curve fitting results present the poor integrity of the substructure. The stiffness and damping constants are much lower than those of well conditioned tracks. This is the noteworthy sign of defect on fastening systems that should be made aware of. In the case of the track with cracked sleeper, the FRF signal presents moderate response level and a number of 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 the substructure, while cracking remarkably increases the damping of system, in terms of increased interlocking frictions in concrete material.

Summary

The degradation of railway track raises a concern on integrity evaluation of railway tracks in the existing conditions. For practical purposes, this paper integrates field measurements, modal analysis, and track simulation in order to develop a NDT approach for the dynamic health monitoring of railway track structures. The railway track is simplified as a 2DOF dynamic system. Optimisation techniques and algorithms for the track model have been developed to extract the dynamic properties of track components from the field measurements using instrumented hammer impact technique.

The advances of this paper are an alternative NDT technique and criteria to evaluate the integrity of track structures. This information is the fundamental concept for dynamic integrity evaluation and for health monitoring of the railway tracks. Three samples that include two major defects found in general track problems, such as damaged e-Clip and a 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 with guidance and as an initial input towards the dynamic analysis of railway tracks for determining the maximum speed and axle load for the future track upgrades or functional changes.

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