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Application of experimental modal testing for estimating dynamic properties of structural components

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Application of Experimental Modal Testing for Estimating Dynamic Properties of Structural Components

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1. Introduction

Of substantial importance in compliant structures, nowadays, are the dynamic parameters such as the dynamic stiffness and damping constant of their components. These parameters are the essential technical information required in engineering analysis and design. In addition, this information is needed for numerical simulations and finite element modelling to predict the response of the structures to a variety of dynamic loadings such as earthquake ground motion, blast and accidental impact loads. Increasing demands of safety and reliability of engineering structures, especially where the dynamic loads are involved, require better understanding of dynamic properties and response of structures. To determine the dynamic characteristics of existing structures, the vibration analysis and testing can be performed.

Experimental modal analysis (EMA) or modal testing is a non-destructive testing strategy based on vibration responses of the structures. Over the past decade, the 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 Fast Fourier Transformation (FFT) technique. Subsequently, the series of FRFs are used to extract such modal parameters as natural frequency, damping, and corresponding mode shape. In a wide 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. In particular, numerous investigations related to aeronautical engineering, automotive engineering, and mechanical engineering have been reported (He and Fu, 2001). Interestingly, not many are involved with structural engineering and dynamics of civil structural systems. In recent years, experimental modal analysis has received wide acceptance in structural engineering application, particularly for identification of modal properties of bridges (Salane et al., 1988), damage detection of structures using modal data (Friswell, 1994; Liu, 1999), structural health monitoring (Cremona, 2004), dynamic FEM updating (Friswell, 1995), active vibration control (He and Fu, 2001), dynamic buckling of structures (Souza and Assaid, 1991), etc.

In this paper, experimental modal testing is used in relation to solving problems in railway engineerin. The railway engineering problem is related to identification of the dynamic properties of the railway track components in laboratory and in-situ conditions. This information is critically needed at the moment, in order to develop the Australian track model. In particular, the modal testing is applied to determine the dynamic stiffness and damping parameters of rail pads of various ages to investigate their degree of degradation with time in service. The frequency ranges used in the tests were different reflecting the range of resonant frequencies and mode shapes important for each specific element. For rail pads used in this study, the frequency range between 0 and 500 Hz is sufficient, while the beam-column elements require a frequency range from 0 to 2,000 Hz. The FRFs were obtained by exciting the specimens with an impact hammer. Bruel&Kjaer PULSE dynamic analyser was utilised for obtaining the FRF measurements and the STARModal package for extracting the modal parameters.

2. Modal Testing

In the 1940s, the modal testing was first developed to investigate the dynamic behaviours of structures using the simple sine dwell method. In the past two decades, a method for modal analysis based on Fast Fourier Transformation (FFT) approach has received the widest acceptance (Brown, 1982; Allemang and Brown, 1986; Mitchell, 1986; Allemang, 1993; Ewin, 1995; He and Fu, 2001). The experimental modal enables engineers to get a better understanding of structural dynamic problems.

There have been many investigations using modal analysis technique, albeit modal analysis is comparatively young. The assumptions include the linearity of structures, time-invariant structural parameters, and observability in measurements (Allemang, 1993). For linear systems, the method of superposition can be used, although the linearity may not be accurate with some structures. The stiffness and damping remain constant, depending on factors excluded in the model, during a time. The input-output measurements should have information enough to develop a characteristic model of the structure. Also, the forcing and receptance functions have to be measurable for the structure to be observed. Methods for performing experimental modal analysis were grouped by Allemang and Brown (1986) into:

- Forced-normal-mode excitation,
- Frequency response function,
- Damped complex exponential response, and
- Mathematical input-output model

The forced-normal-mode function method is the first modal testing technique that uses multiple inputs to estimate the modal parameters. It however does not consider the complex modes of vibration. The frequency response function method is very common at present. It contains spectra calculated from the auto-spectrum and cross-spectrum that are recorded from the structure. The damped complex exponential response method is a technique using the information acquired from the free decay of a system generated by the free oscillation by imposing an initial condition. There are two similar approaches, which are the Ibrahim time domain method and the Poly reference approach. The mathematical input-output model method independently takes the input and output responses into consideration. The applications of this method can apply to both time and frequency domain models with an unlimited number of degrees of freedom (dofs). Other techniques, which are based on this methodology, are the autoregressive moving average approach and the reduced structural matrix approach (Allemang and Brown, 1986).

3. Application to Rail Bearing Pads

In the traditional ballasted track system, rail pads, usually made from polymeric compound materials, are mounted on rail seats and used to attenuate the dynamic stress from wheel/rail impact from both regular and irregular movements. Figure 1 shows an example of a resilient pad employed in this study. Its profile is of the studded type.

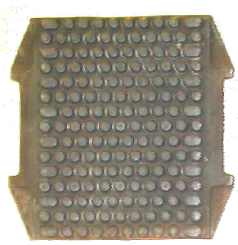

Figure 1 Example of studded rail pad profile.

3.1 Analytical Modal Analysis

Remennikov and Kaewunruen (2004) derived an analytical dynamic transfer function of rail pads idealised as a simple mass-spring-damper SDOF system. The magnitude of the frequency response function $H(f)$ (Nm/s^2) is given in terms of frequency f (Hz) by

$$H(f) = \frac{1}{m} \frac{4\pi^2 \left(\frac{m}{k}\right) f^2}{\sqrt{\left[1 - 4\pi^2 \left(\frac{m}{k}\right) f^2\right]^2 + \left[4\pi^2 \left(\frac{m}{k}\right)\left(\frac{c^2}{km}\right) f^2\right]}} \quad (1)$$

where *m*, *c*, and *k* generally represent the effective mass (kg), damping value (Ns/m), and stiffness (N/m) of rail pad, respectively. Based on Eq.(1), these dynamic parameters are extracted from modal data measured in the laboratory or in the field.

3.2 Experimental Modal Testing

An experimental rig for dynamic testing of rail pads has been developed at the University of Wollongong. The test rig shown in Figure 2 consists of a concrete block that supports a short length of steel rail, e-Clip fastening system, and a rail pad. The concrete block is attached to a strong floor to simulate the absolutely rigid foundation. An accelerometer is installed at the railhead, as illustrated in Figure 2. An impact hammer is used to excite the assembly of components. The frequency response function (FRF) is then acquired using the PULSE dynamic analyser in a frequency range from 0 to 500 Hz. The coherence function representing the degree of linearity between the input and output signals and therefore the quality of FRF measurements can also be acquired. In this case study, the properties of the PANDROL resilient rubber pad (studded type, 6.5 mm thick) have been identified using the test rig. The case study results are presented in Figure 3. The magnitude of FRF (Figure 3a) and the corresponding coherence function (Figure 3b) are also presented.

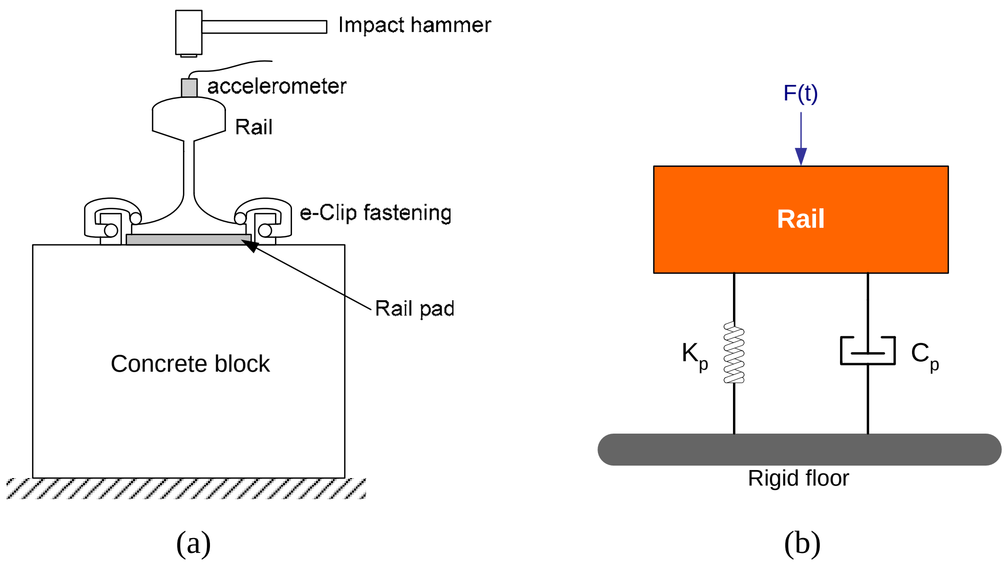

Figure 2 Experimental rig for testing rail pads: (a) test rig; (b) modeling.

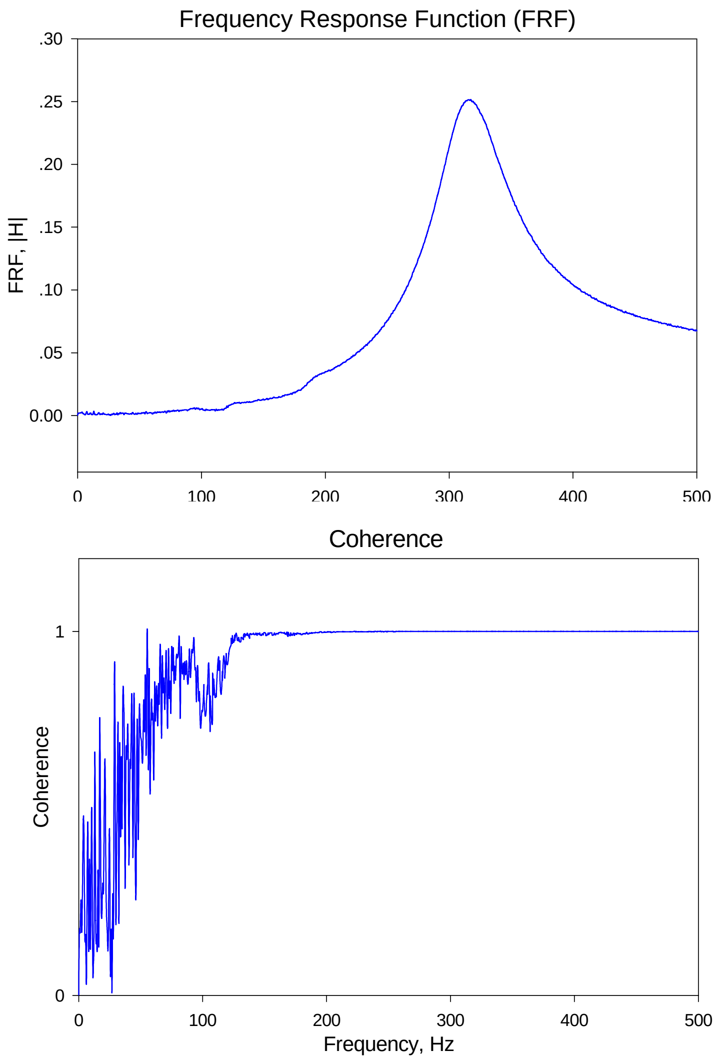

Figure 3 Results of modal testing: (a) frequency response function for a rail pad; (b) coherence function..

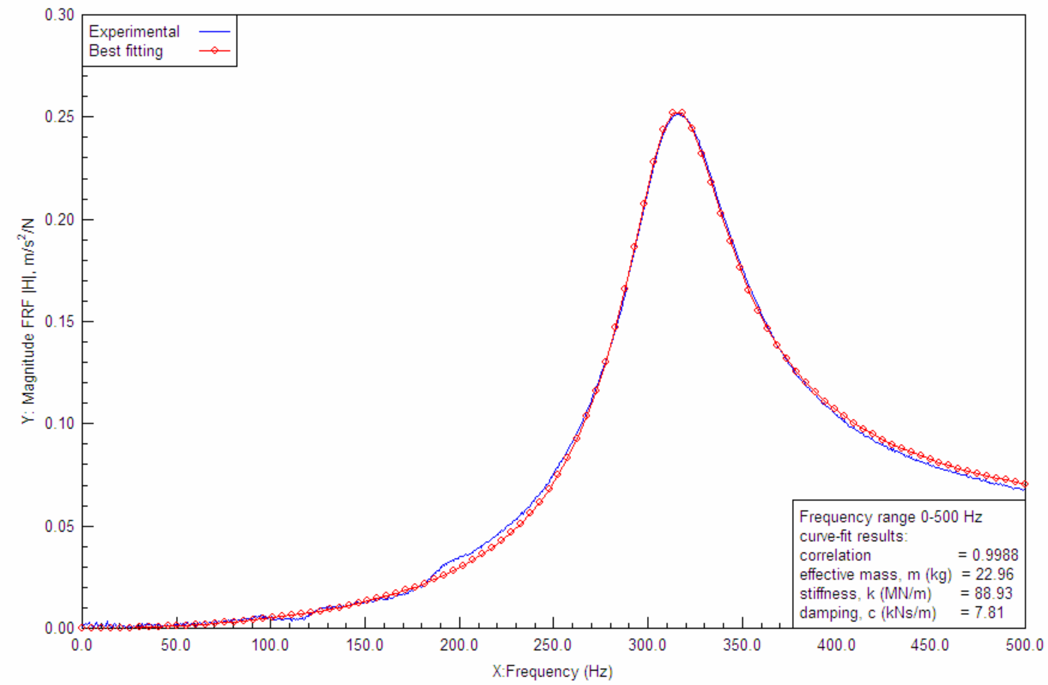

Figure 4 Curve fitting of frequency response function.

3.3 Results

The best curve-fitting approach is used to extract the dynamic properties of rail pads. An analytical expression for FRF of a SDOF system is used to curve fit the results of experimental measurement of FRF using the least squares method. Curve-fitting algorithms can be found in many general computational packages (e.g. MATLAB, Mathematica, Maple), or using specialised curve-fitting computer codes (e.g. DataFit). Figure 4 demonstrates the curve fitting performed by a computer program DataFit and gives some modal parameters that are close to the industry specifications (Remennikov and Kaewunruen, 2004). An excellent agreement between the analytical and experimental data is demonstrated by the value of the correlation coefficient r^2 which is 0.9988. The modal testing has proven to be a fast and effective test method for identification of the dynamic stiffness and damping constant of rail pads. The developed technique can lead to a more comprehensive study of condition assessments of rail pads at different ages and under different working conditions. For example, FRFs obtained from aged pads used in NSW rail network is presented in Fig.5.

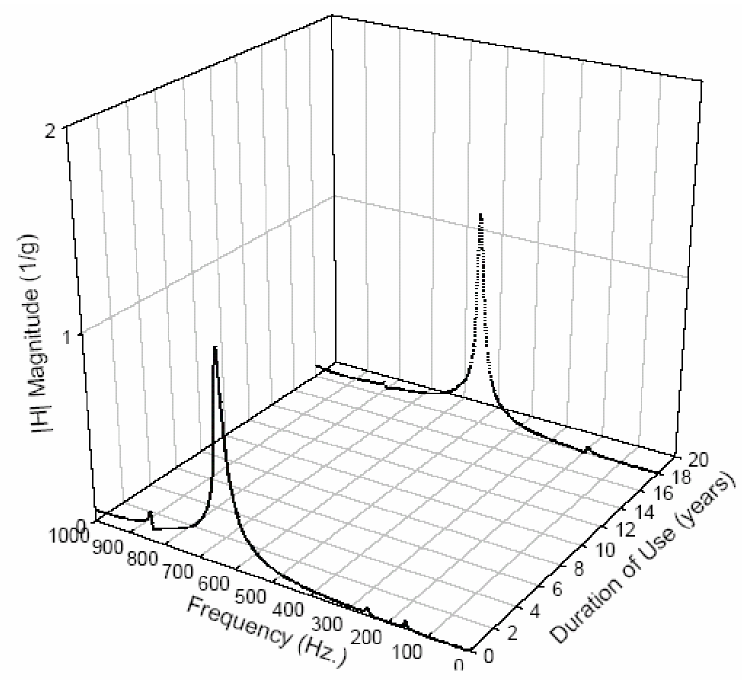

Figure 4 Frequency response functions of aged rail pads.

4. Conclusion

The dynamic parameters such as the dynamic stiffness and inherent damping value of their components are very important in compliant structures. Modal testing is a non-destructive testing strategy based on vibration responses of the structures. In this paper, the application of experimental modal testing to a railway track component is demonstrated to assess the effective dynamic stiffness and damping constant of these examples. The modal testing has proven to be an effective and non-destructive test method for estimation of the dynamic stiffness and damping constant of the track component. Applications of modal testing to structural members also involve with determining modal properties of a variety of structural beams (Chowdhury, 1999; Salzmann, 2002) or with identifying the connection rigidity of the structures (Kohoutek, 1995).

5. Acknowledgement

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