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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 in 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.



Figure 1: Typical ballasted track on a coal line in Central Queensland (after [7])

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.

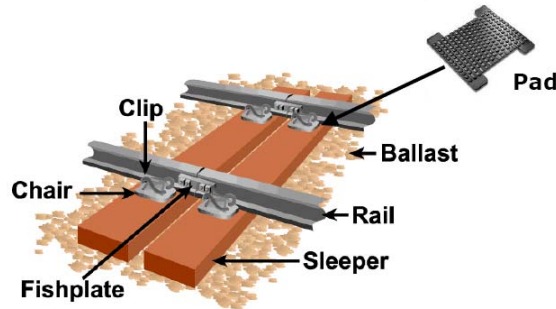


Figure 2 Typical ballasted tracks

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

Finite element model	2DOF mass-spring system
<p style="text-align: center;">FEM</p>	
<p style="text-align: center;">in-phase vibration</p>	
<p style="text-align: center;">out-of-phase vibration</p>	

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.

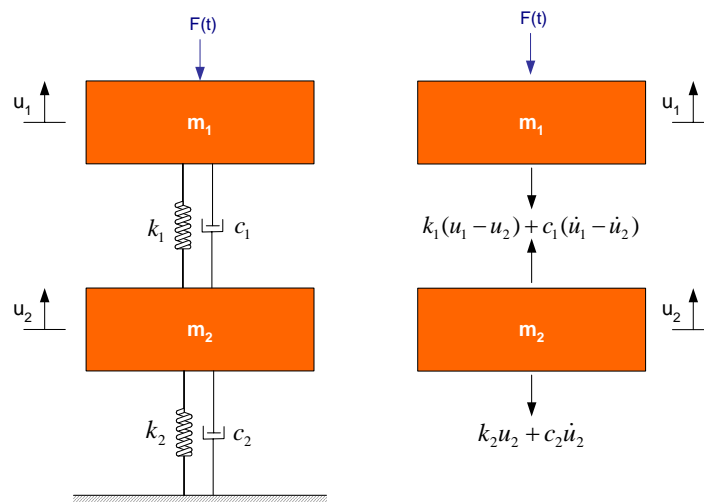


Figure 3: 2DOF dynamic models of railway track



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.

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

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

4. Condition assessments

The field measurements produced the FRF data sets to be processed for assessing the structural conditions of the railway track. Figure 5 shows the example of FRF measured in the field within a frequency range from 0 to 1600 Hz. The coherence functions were also recorded for each FRF so that the quality of vibration measurements could be evaluated (see Figure 5 (b)). Based on the previous experimental work [7], the frequency range of 0 to 800 Hz was of practical interest in this study. The in-phase and out-of-phase resonance frequencies were found to about 130 Hz and 520 Hz, respectively.

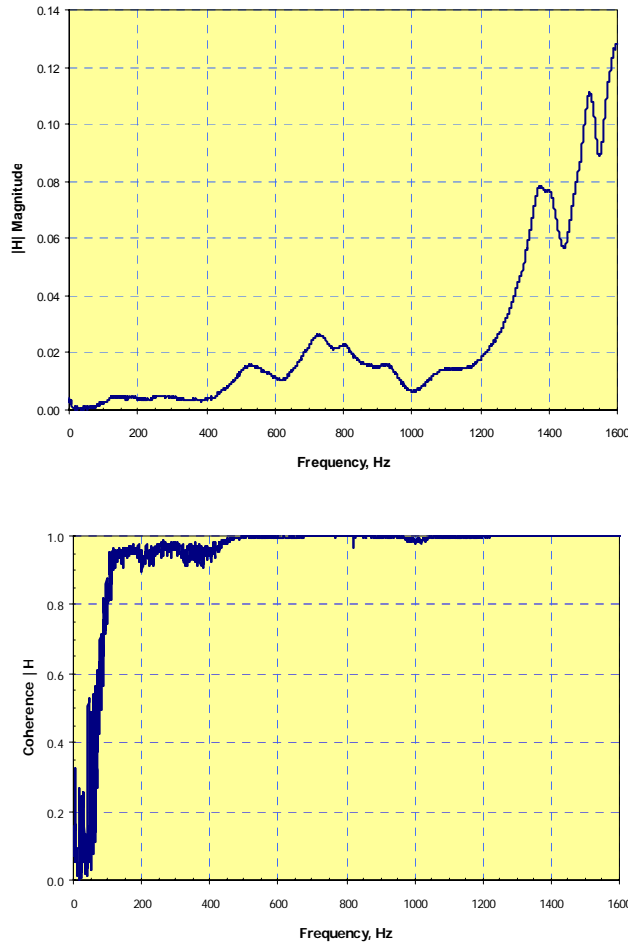
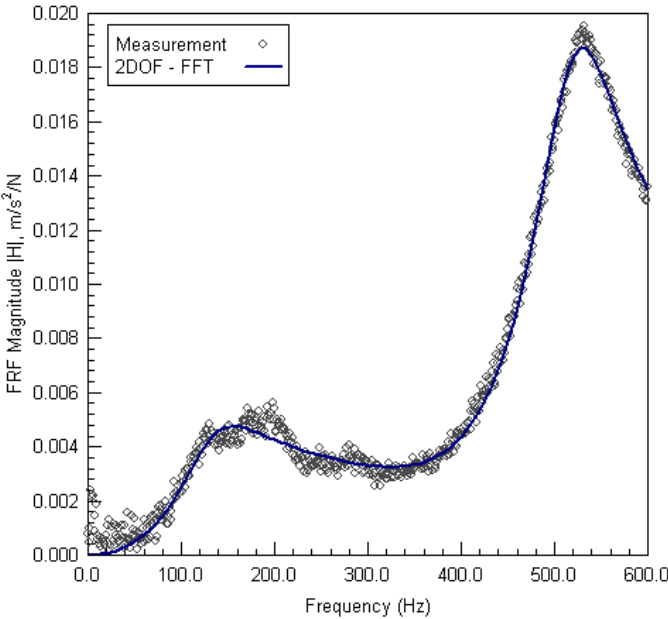
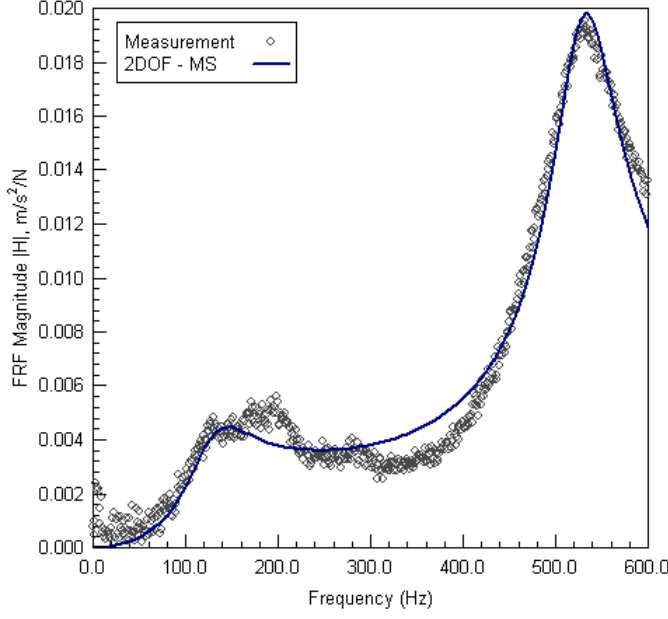


Figure 5: Dynamic measurements at Sleeper C0

The data sets obtained from field measurements were processed using two approaches: FFT and MS. The curve fitting operations were done using a curve-fitting package DataFit [13]. An example of the curve-fitting results is presented in Figures 6(a) and 6(b) for the two analytical approaches used. The actual dynamic properties of the railway track of six consecutive sleepers tested at Site C are tabulated in Table 2 and Table 3 using FFT and MS formulae, respectively. From the results, it can be seen that the correlation error of the curve fitting is less than 3% for FFT procedure and 5% for MS algorithm. The results obtained using both approaches were in a good agreement with the industry-accepted data used in track design. Also, the results obtained are consistent for all tested sleepers. Using FFT, the stiffness of pads was found to be about 850-1050 MN/m, whereas the MS algorithm resulted in 1,100-1,500 MN/m. The ballast stiffness was determined to be within range of 140 to 270 MN/m using both FFT and MS techniques. The damping constants for rail pads varied from 1 to 23 and 1 to 58 kNs/m based on FFT and MS, respectively, while the damping values of ballast varied from 140 to 270 kNs/m based on both FFT and MS. It was found that the damping coefficients of the track components tested were in the acceptable ranges. Table 4 summarizes the average parameters of railway track components determined in the field investigations. Overall, the conditions of railway track components could be considered acceptable since the stiffness of rail pads and their damping characteristics have not deteriorated below the industry acceptable limits.



a) FFT Best Fitting



b) MS Best Fitting

Figure 6: Best curve fitting of measured data at C1

Table 2 Summary of dynamic properties of track at Site C (FFT)

Site (0-800Hz.)	Correlation r^2	Upper Part		
		C_{pad} (Ns/m)	K_{pad} (N/m)	M_{rail} (kg)
C-1	0.990370	6,696.00	1,045,412,190.0	179.9783
C0	0.977459	6,933.48	956,950,777.9	177.3152
C1	0.993433	1,339.77	963,410,355.7	168.9247
C2	0.972611	1,000.00	892,737,413.4	146.1906
C3	0.992181	7,486.26	865,471,146.1	161.9415
C4	0.984155	23,384.45	891,949,856.1	165.4077
C5	0.977438	19,175.90	861,030,098.9	162.7145
Site	Correlation r^2	Lower Part		
		$C_{ballast}$ (Ns/m)	$K_{ballast}$ (N/m)	$M_{sleeper}$ (kg)
C-1	0.990370	269,838.26	362,291,925.7	227.0179
C0	0.977459	241,633.38	284,009,399.4	194.2615
C1	0.993433	254,295.62	282,214,086.0	204.4043
C2	0.972611	254,754.35	271,532,453.0	184.2976
C3	0.992181	204,785.97	191,056,528.5	183.9790
C4	0.984155	180,065.38	177,804,410.5	181.1320
C5	0.977438	174,511.72	159,019,491.8	180.3394

Table 3 Summary of dynamic properties of track at Site C (MS)

Site (0-800Hz.)	Correlation r^2	Upper Part		
		C_{pad} (Ns/m)	K_{pad} (N/m)	M_{rail} (kg)
C-1	0.969479	6,696.00	1,418,203,265.0	231.5371
C0	0.967322	6,933.48	1,277,246,261.0	223.7322
C1	0.979897	1,339.77	1,292,605,498.0	215.1528
C2	0.960563	10,702.53	1,188,380,629.0	179.6050
C3	0.974948	7,486.26	1,203,131,040.0	210.9832
C4	0.961227	23,384.45	1,318,711,646.0	228.8367
C5	0.956606	58,520.54	1,508,791,360.0	227.0675
Site	Correlation r^2	Lower Part		
		$C_{ballast}$ (Ns/m)	$K_{ballast}$ (N/m)	$M_{sleeper}$ (kg)
C-1	0.969479	274,226.41	474,110,486.2	316.9277
C0	0.967322	234,870.40	356,154,073.0	263.0448
C1	0.979897	258,237.77	366,577,836.8	285.5814
C2	0.960563	247,726.41	306,363,264.3	264.7573
C3	0.974948	209,516.46	261,572,589.7	261.5971
C4	0.961227	172,935.74	263,628,094.2	263.7609
C5	0.956606	146,423.48	307,018,540.2	381.4028

Table 4 Summary of average parameters of the railway track components

Track Components	Methodologies	Average Parameters	
		Damping (kNs/m)	Stiffness (MN/m)
Rail pad	FFT	9.430	925.280
	MS	16.438	1,315.296
	FFT+MS	12.934	1,120.287
Ballast	FFT	225.698	246.847
	MS	220.562	333.632
	FFT+MS	223.130	290.240

5. Conclusion

Accelerating degradation of railway track creates many problems for railway track 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. The in-field dynamic testing in combination with track modeling represents an efficient strategy for identification of the current condition of railway track structure and its components.

In the field investigations described in this paper, the experimental modal testing was employed. 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 finite element modelling to evaluate the dynamic parameters of in-situ railway track components. Based on the discrete support model, the railway track is simplified as a two-degree-of-freedom (2DOF) dynamic system. Analytical formulation of the 2DOF model has been developed in order to extract the modal properties of 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) has been selected to perform the field tests. Six sleeper-fastening-rail assemblies have been randomly selected for dynamic testing. 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 500 Hz is sufficient in the optimisation. The data collected in that frequency range have been simulated using least-square curve fitting to determine the dynamic stiffness and damping constants of the tested track components.

Based from the analysed results, the correlation of the curve fitting seems to be very good in both methods: FFT and MS. However, FFT tend to better fit the experimental data. The dynamic properties at this site are consistent as can be seen that the stiffness of pad and ballast lies in the narrow ranges: 800-1500 MN/m for rail pads and 150-470 MN/m for ballast. Nonetheless, the damping for rail pads is varied from 1 to 58 kNs/m and for ballast is from 140 to 270 kNs/m. The conditions of railway track can be considered very good since the pad stiffness is still high and the damping does not drop much. These results can supply a track maintenance engineer with very important information on the current state of the railway track and also as the benchmark for health monitoring. In addition, the experimentally determined resonance frequencies along with the dynamic properties of the track components can provide an important 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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References

- [1] Andersson, M., Murray, M., Ferreira, L., Lake, N., (2004), Collection and use of railway track performance and maintenance data, CORE 2004 – Conference on Railway Engineering, Darwin, Australia.
- [2] Esveld, C., (2001), Modern railway track, 2nd edition, MRT Publication, The Netherlands
- [3] De Man, A.P. (1996). "Determination of dynamic track properties by means of excitation hammer testing", Railway Engineering International 1996 Edition, (4), 8-9.
- [4] De Man, A.P. (2002). "DYNATRACK: A survey of dynamic railway track properties and their quality", Ph.D. Thesis, Faculty of Civil Engineering, Delft University of Technology, The Netherlands.
- [5] Esveld, C. (1997). "Track structures in an urban environment," Proceedings of Symposium K.U. Leuven, The Netherlands. 1-21.
- [6] Esveld, C., Kok, A.W.M, and De Man, A. (1998). "Integrated numerical and experimental research of railway track structures", Proceedings of the 4th International Workshop on Design Theories and their Verification of Concrete slabs for Pavements and Railroads, Portugal.
- [7] Kaewunruen, S. and Remennikov, A. (2005), "In-field dynamic testing and measurements of railway tracks in Central Queensland", March-June Research Report, CRC Railway Engineering and Technologies, Australia.
- [8] Timoshenko, S. (1926), "Method of analysis of statistical and dynamical stresses in rail," Proc. Second Int. Congress for Applied Mechanics, Zurich, 407-418.
- [9] Grassie, S.L. and Cox, S.J. (1984). "The dynamic response of railway track with flexible sleepers to high frequency vertical excitation", Proceedings of Institute of Mechanical Engineering Part D, 24, 77-90.
- [10] Cai, Z. (1992), "Modelling of rail track dynamics and wheel/rail interaction", Ph.D. Thesis, Department of Civil Engineering, Queen's University, Ontario, Canada.
- [11] Knothe, K. and Grassie, S.L. (1993). "Modelling of railway track and vehicle/track interaction at high frequencies", Vehicle System Dynamics, 22(3-4), 209-262.
- [12] De Man, A.P. (1996). "Determination of dynamic track properties by means of excitation hammer testing", Railway Engineering International 1996 Edition, (4), 8-9.
- [13] DataFit, User's Manual, Oakdale Engineering, Oakdale, PA, USA.