Dynamic Track Modulus from Measurement of Track Acceleration by Portancemetre

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Abstract
The measurement of track stiffness is an important parameter for assessing the condition of a railway track. This paper describes a method by which the dynamic track stiffness can continuously be determined from the displacements of the track and the applied force using the demonstrator of the Railway Portancemetre. The technique used for calculation of the displacement, and the force is based on the measured acceleration due to the vibrating wheel. The direct force-displacement (FD) curve method for calculating the stiffness is described. Results indicate that the viscoelastic response of the soil and the excitation frequency will influence the value of track stiffness determined using the FD method. Data from the experimental and real site of railway track with different excitation frequencies are used to explore and quantify the functionality of the system in the field.

Introduction
The performance of a railway track depends on the interaction between the track support (including the subgrade, any subballast and the ballast), the track superstructure (comprising the rails, fastening system, and sleepers) and the train vehicles. Historically most attention has been paid to the functionality of the train and the superstructure, as these may be easily inspected and maintained to ensure optimum performance.

Poor track support can result in the decrease of track geometry quality, leading in turn to an increased vehicle loading and track damage. Both may feed back into further geometry degradation, resulting in an accelerating cycle of track system deformation and damage or more maintenance requirement.

Most maintenance strategies use track geometry as the major diagnostic parameter, with corrective measures predominantly involving tamping of the ballast to restore track geometry to within acceptable limits as the need arises. However, the performance of the ballast is heavily dependent on the subgrade performance, and ballast tamping does not correct a poor subgrade. Thus there is a tendency for track geometry defects associated with an unsatisfactory subgrade to reappear regularly.

To optimize and extend the range of maintenance procedures, a better knowledge of subgrade performance is required. This is even more important for today’s railways as axle loads, train speeds, and track utilization increase.

An important parameter for characterizing the structural condition of the track support is the track stiffness. Although there are various definitions of track stiffness, all are based on a relationship between the vertical displacement of the track and the applied load causing it. A number of different techniques have been developed based on static loads and rolling measurements using specially adapted vehicles or trains. This paper describes a method of determining a measure of track stiffness continuously along the track using the Railway.

Railway Portancemetre construction

Final design draft
During the Innotrack project (D2.1.9 INNOTRACK 2009), the schematic model of the demonstrator was approved and the construction of the apparatus was started. In order to respect the delivery time and reduce the costs of the system, the principal of the Portancemetre construction is programmed into two parts: one part is the measurement core system called demonstrator and the other part was the technical carriage system. Figure 1 shows the general principle of the study of the demonstrator and the technical carriage.
Producing the dynamic force is guaranteed by two unidirectional vibrators installed on the unsprung mass. Both vibrators generate a controlled vertical acceleration. The horizontal component of the force generated by the vibrators will be cancelled by the reverse rotation effect of the eccentric mass in each vibrator.

For the demonstrator project, the technical carriage is just designed to carry the power supply devices (Figure 1). So, a bogie was used as a simple platform adapted to support and carries the hydraulic group and the electronic systems. The system was designed to be pulled by one locomotive attached to the technical carriage and towing the demonstrator.

Demonstrator construction
A wheelset of type 417 is selected as the core of unsprung mass. The unsprung and suspended masses uncoupled by the visco-elastic connection system.
For the technical carriage system, a bogie of type Y25C was renewed and tested in the SNCF maintenance workshop at Sotteville. All construction and assemblies of the technical carriage frame are realized at the CETE.
The demonstrator was instrumented by different sensors listed bellow:

- Unsprung mass accelerometer: to measure the unsprung mass acceleration these sensors were installed on the axle (wheelset).
- Chassis accelerometer: to measure the suspended mass acceleration these sensors were installed on the suspended frame.
- Phase sensor (synchronization signal): to point out the rotation of the eccentric axis of vibrators, these sensors were installed on the vibrators’ output signals.
- Incremental distance encoder: to measure the traveled distance this system was positioned on the axis of the technical carriage bogie.

Figure 2 shows a detailed view of the different sensors installed on the railway Portancometre.
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The complete data acquisition chain is constituted of all sensors, the electronic Analog/Digital converter and the necessary hardware and software system.

A camera with a linear CCD sensor is mounted under the technical carriage to record and monitor the measured track surface. At this time, the recorded film will be treated by post processing software, and the results will be superimposed on the measured data. All measurements are checked and monitored from the portable computer which is placed in the locomotive. The supervisor software is equipped with a data geo-positioning (Sat.Nav).

The Figure 3 represents the completely assembled railway Portancemètre while working on the real site at Rouen (D2.1.9 INNOTRACK 2009).
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Testing of Railway Portancemètre demonstrator

Site CETE: set-up tests
After completion of the construction, the demonstrator was tested on a fixed point on a portion of the track section at CETE (Figure 4). The demonstrator was positioned on the track by a road crane.

![Figure 4: Preliminary tests on track section at CETE](image)

These tests were realized on a fixed point to verify the good functioning of the system as a whole. The tests were carried out in the initial configuration of the vibrators with the maximum frequency of vertical excitation of 25 Hz. Based on the tests results, it could be concluded that the excitation frequencies higher than 15 Hz are more interesting.

This site consisted of 50 kg/m rail on timber sleepers. This track was constructed at CETE NC for an initial and setup test to give indication of stiffness variations from variation of excitation parameters. The structure consisted of a 25 cm clean ballast with the particle size of 31.5/50 mm and a subgrade of clayey sand.

Site "Des Jardins": rolling test on real track
This site was situated on the "Port Autonome" branch line, at Rouen. The site consisted of 54 kg/m rail and the timber sleepers. The selected section was about 1200 m long. The site was chosen to give indications of stiffness variations from formations with clean and fouled ballast with different ballast thickness. A cross section of Site "Des Jardins" and his plan view are shown in Figure 5.

![Figure 5: Des Jardins test track site](image)
The direction of the measurement is from A to D (Figure 5) with the measurement error of localization about 1%. The kilometic points for the test track are: point A at PK1 + 830 m, point B at PK1 + 345 m, point C at PK1 + 098 m and point D at PK0 + 812 m. The Figure 6 represents the test track and installation of the Portancemetre.

Figure 6: Des Jardins Test track and installation of the Portancemetre

Panda measurements
On the Des Jardins track, 24 measuring points with Penetrogram (PANDA) were made (AFNOR 2000). The test points are positioned between the point A and D (Figure 5).

The results show peak resistance variations, which are very heterogeneous. The PANDA measuring apparatus and a typical example of PANDA are shown in Figure 7.

Figure 7: Measurement with Penetrogram (PANDA)

Measurements the trackbed stiffness by the Road Portancemetre
Figure 8 shows the measurement of trackbed modulus with the Road Portancemetre (Guide 2008) on the right side of the test track (from B to D for a length of 545 m). The obtained results are presented in Figure 8 with the variation of modulus between 50 and 70 MPa.
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Road Portancemetre | Modulus measurement over a section of the Des jardins track (between the points B and D)

Figure 8: Trackbed stiffness measurement by the Road Portancemetre

**Track stiffness definition and calculation**

The vertical track stiffness (k) can be defined in different ways (Hosseingholian et al. 2006). A simple and straightforward definition in the time domain is known as the beam-on-elastic-foundation method, or the Winkler method. A vertical force F(t) applied by a wheel produces a vertical rail deflection z(t). Therefore, the track stiffness (k), taken at a point as the wheel passes directly overhead, is defined as:

\[
k(t) = \frac{F(t)}{z(t)}
\]

(1)

Knowing that, the model has a number of practical shortcomings (Crawford et al. 2001). Using a single axle load (wheelset) minimize the impact of other loads in case of a wagon test. Following this definition we can classify the tangent and secant stiffness for the loading and unloading phases. It is obvious that the various components of the track have more or less a non-linear behavior, such as soil and rail pad. In many cases, the sleepers can also have non-uniform contact with the ballast, which leads to large settlements under a low load. This will in turn create a few other definitions of track rigidity. The stiffness that is often used to eliminate the bad behavior during the contact, is the secant stiffness calculated between two force values selected relative to the maximum applied force, as:

\[
k_{ab} = \frac{\Delta F}{\Delta z} = \frac{F_b - F_a}{z_b - z_a}
\]

(2)

Where, ΔF and Δz are the difference between the values obtained at two predefined points in time respectively ("b" and "a" may be selected based on various definitions).

The total applied force (FTA) per rail is calculated as equation 3 (Guide 2008).

\[
FTA = M_g \dot{g} + M_v \dot{\Gamma}_b + M_c \dot{\Gamma}_c + m_e \omega^2 \cos \phi
\]

(3)

in which, M_g is the unsprung mass, M_v is the suspended mass, Γ_b is the vertical acceleration of the wheelset (unsprung mass), Γ_c is the vertical acceleration of the chassis (suspended mass), "m.e" is the eccentric moment of the unbalanced system, ω is the angularity velocity and φ is the angle of rotation.
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The double integration of the vertical acceleration of the unsprung mass, $\Gamma_b$, equals the vertical displacement $z$, (Eq. 4).

$$z(t) = \int \int \Gamma_b(t) dt$$  \hspace{1cm} (4)

The total applied force, FTA, and the corresponding deflection, $z$, allow a determination of the stiffness, $k$, over an average time period (Robinet et al. 2008).

Figure 9 illustrates the typical Force-Displacement curves of track subjected to dynamic excitation as measured on "Des Jardins" track during the test of the railway Portancemetre. The static and dynamic force per rail was about 50 kN and 20 kN respectively. The curve is non-linear and also features hysteresis, which indicates damping. By considering the stiffness as constant in time and place, the average value of the stiffness was calculated. This is of course not valid in the time domain or in the frequency domain with a high degree of accuracy.

![Vertical force-displacement curve of "Des Jardins" track](image)

**Figure 9:** Vertical force-displacement curve of "Des Jardins" track

### Railway Portancemetre testing results

About 20 measuring sessions were undertaken on Des Jardins site. Half of these sessions were performed on the whole track length (1000 m) and the other on a reduced zone on which the Road Portancemetre and PANDA have been used. The running speed of the Portancemetre during the tests was 6 km/h. During these tests the different frequencies and dynamic forces were tried. Three different configurations of equipment were used as shown in Table 1. The calculated stiffness value was then averaged for about 1 m of traveled distance.

<table>
<thead>
<tr>
<th>Test modality</th>
<th>Unsprung mass (kg)</th>
<th>Suspended mass (kg)</th>
<th>Eccentric moment (m.kg)</th>
<th>Excitation frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-2 me100</td>
<td>2940</td>
<td>2955</td>
<td>1.391</td>
<td>20, 25, 30</td>
</tr>
<tr>
<td>4-0 me60</td>
<td>1800</td>
<td>2955</td>
<td>0.835</td>
<td>30, 25, 30, 35</td>
</tr>
<tr>
<td>4-0 me40</td>
<td>1800</td>
<td>2955</td>
<td>0.556</td>
<td>10, 20, 25, 30</td>
</tr>
</tbody>
</table>

**Table 1:** configuration of equipment used on Des Jardins test site

**Data treatment**
Figure 10 shows typical examples of accelerations of the unsprung and suspended masses measured during the tests. The acceleration of the vibrating wheel is smooth (without noise). In reality, there are important disturbing noises in the recorded signals of the suspension accelerations. Indeed, in the second phase of the research we will continue to develop the mechanical and electronic system to remove the sources of distortion and to improve the quality of the recorded signals. But for the time being numerical filtering was used as a solution to reduce noise and to prepare the signals for analysis. The typical results of such numerical filtering are presented in Figure 11. For this research, a low pass filtering at 45 Hz was chosen and to avoid phase delay related to the filtering a cosine wave was used as a reference signal.

![Unsprung mass acceleration record](image1)

![Suspension mass acceleration record](image2)

**Figure 10**: Typical example accelerations of unsprung and suspended masses measured by Railway Portancemetre, raw data recorded directly

![Unsprung mass acceleration record](image3)

![Suspension mass acceleration record](image4)

**Figure 11**: Typical filtered accelerations of unsprung and suspension masses measured by Railway Portancemetre, low pass filtered
Phase delay
The variation of the stiffness along the track is the most common quantity to characterise mechanical situation of the track. Figure 12 illustrates the phase delays between load and displacement with different excitation frequencies. It shows how long it takes for the track to respond to the applied load. The phase delay depends on the mechanical characteristics of the structure as well as the excitation parameters. It can also be regarded as a damping of the system, but to calculate actual values of this damping, a mechanical model of the track must be used.

![Figure 12: Illustration of phase delays between normalized force and displacement](image)

Repeatability test
Figure 13 displays a repeatability test on the "Des Jardins" track, a section of approximately one km has been tested two times with the same speed and excitation frequency. In these tests, the running speed and the excitation frequency was 6 km/h and 30 Hz, respectively. Each value of stiffness represents a mean value over 30 periods of excitation. The figure presents the raw data without any correction, so the disturbance of the values at the beginning of the figure is a result of the time it takes for the system to start normal measurements. The maximum standard deviation between two measurement runs is about 0.6 kN/mm. The repeatability is therefore, considered as very good with the p-value greater than 5% based on the ANOVA statistic test. The very high values indicate the intersection of track with the water channels or culverts crossing the railway track.
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Figure 13: Repeatability test of continuous track stiffness measurements, with a speed of 6 km/h and an excitation frequency 30 Hz

Variability of modulus with traveling speed

Figure 14 represents results from tests with different running speeds from 3 to 10 km/h and 30 Hz of excitation frequency. Here again, the stiffness values are the mean value of 30 cycles. There are minor differences in measured-stiffness between the different tests which can be considered negligible. So at a low speed there is not any important influence in the measured stiffness.

Figure 14: Continuous track stiffness measurement at different running speeds
Variability of modulus with excitation frequency

Figure 15 shows the stiffness results of different tests with various excitation frequencies and a running speed of 6 km/h. The stiffness values are always the mean value of 30 periods. Clearly, there are important differences between 25 Hz and other excitation frequencies. This may be explained as the 25 Hz being too close to the resonance frequency of the track but this must be verified by complementary tests and analyses. On the other hand, the results of from 10 Hz and 30 Hz excitations (we may suppose that these are the frequencies before and after the resonance) are significantly close to each other especially for low values of the stiffness. An analysis of the results and the complementary test may clarify this phenomenon.

![Figure 15: Continuous track stiffness measurement at different excitation](image)

Conclusions

Track stiffness is a useful parameter in the assessment of track performance and condition, and in planning the maintenance. A method has been proposed for continuous measurement of the track stiffness, which uses accelerometers attached to the apparatus to record the acceleration of the unsprung and the suspended masses.

The demonstrator version of the Railway Portancemètre as a new method of continuous track stiffness measurement running directly on the rail has been presented. The method has proven significant repeatability, and it seems that there is a good correlation with other existing methods. The ability to change excitation frequency, dynamic load and running speed is a strength of the method and gives the possibility to study the mechanical behavior of the track. The concept of excitation frequency also puts demands on using the correct interpretation. The measurement method has the potential of giving the track engineer deepened knowledge about the railway structure and together with another knowledge, like track deterioration, can lead to a more cost-effective maintenance.

References


D2.1.9 INNOTRACK. (2009). D2.1.9 Adapted "Portancemetre" for track structure stiffness measurement on existing tracks. Paris.

