# A NUMERICAL TOOL TO ASSESS THE DYNAMIC BEHAVIOUR OF DIFFERENT TRACK DESIGNS

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# A NUMERICAL TOOL TO ASSESS THE DYNAMIC BEHAVIOUR OF DIFFERENT TRACK DESIGNS

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ABSTRACT
Receptance tests are widely used, *in-situ*, to get information experimentally on the global dynamic behaviour of tracks. As a complement to this measurement, numerical models can be of great use to the diagnose of existing tracks, especially in zones presenting unexpected response to passing trains or in zones with specific design, providing a more detailed mechanical response.
The Dynavoie software used in this paper is a finite element model which aims at offering a comprehensive view of the global track response, taking into account both track and platform. In the developed approach, all the components of the system, from the rail to the soil are of interest. This global approach combined with the low computation time due to the reduction strategy is specificity of the software.
This paper presents an experimental and numerical work on receptance tests. Receptance test measurements carried on an existing track are first presented. Then, the same track is analysed in the frequency domain using the numerical model described above. Finally, the model is used to understand the link between the frequency behaviour of the track and its dynamic behaviour to moving load in the time domain.

INTRODUCTION
Mainly designed on empirical bases, railway tracks are complex mechanical systems and their dynamic behaviour is still not fully understood. A widespread mean to get insight into the dynamic behaviour of the track is to characterize its behaviour in the frequency domain. This can be experimentally done via the receptance test (Knothe & Wu 1998). Even if this test gives a good picture of the track dynamic behaviour at the superstructure level, it does not provide a specific understanding of the contribution of each component to the global response. At this stage, the use in addition of a numerical tool able to describe wave propagation in the layers can complete the receptance test interpretation (Arlaud et al. 2015). Different numerical models provide such insights.
Various authors (Hall 2003; Kouroussis et al. 2011; Thach et al. 2013; Connolly et al. 2014 among others), have proposed an approach based on 3D Finite Element Method (FEM) to model induced vibrations in railway tracks. Specific attention has to be paid to the boundaries: they have to be adapted to avoid spurious wave reflections. The main drawbacks of these models are the large computational time and the large storage capabilities required. To address these issues, some authors (Yang et al. 2003; François et al. 2010; Alves Costa et al. 2012 among others) have proposed models coupling finite element and boundary element methods in 2.5 D. They considered a track section, taken as invariant in the track developing direction, and solve movement equation using spatial inverse Fourier transform, which implies approximations on the track geometry (the rail is modeled as continuously supported by sleepers and no variation in the track geometry can be considered). A similar approach is to use Floquet transform and to represent the whole problem in one generic cell in 3D accounting for the periodicity of the track (Chebli et al. 2008). The finite element model Dynavoie (Ferreira & López-Pita 2015), used in this work, is inspired by this last category. It presents a hybrid approach between 2.5D FEM calculation and 3D FEM and uses model reduction techniques.
In this paper, receptance measurements carried on a French high speed line are presented and the results are analysed using the Dynavoie model. The link with time domain results is also discussed.

EXPERIMENTAL SETUP

Experiment description

Hammer impact on structures is a widespread way to get information on their dynamic behaviour (Oregui et al. 2014) and the main advantage is that it is a non-destructive test. Applied to railway, it consists in an impact on the top of the rail, in order to get information on the frequency behaviour of the railway track as a global system. Receptance shows the vibration amplitudes of the track as a function of the vibration frequencies (De Man 2002). This test measures the displacement of the rail at the point where an impact is imposed. It gives a characterization of the track stiffness variations with frequency. The range of frequency studied depends on the size of the hammer. Using a small hammer one can reach frequencies up to 3 kHz and therefore use this experiment to detect rail defects (Oregui et al. 2014). When using a bigger hammer, lower frequencies are reachable, and then, below 400 Hz, the receptance curve shape depends mainly on the properties of the subgrade and of the ballast layer (Knothe & Wu 1998).

Test site description

Receptance tests have been performed in the French East European high speed line between Paris and Strasbourg. As this line is currently operated, measurements were performed during a night interception. A specific zone, presenting four different track designs has been chosen in order to verify experimentally that the changes in the substructure are visible in the receptance curve.

This track portion is a transition zone between ballasted track and slab track in Chauconin as displayed in Figure 1, the main properties are recalled hereafter, a more precise description can be found in (Costa d'Aguiar et al. 2015).

Measurements are performed in the following four different zones:

i. The ballasted track: this zone presents the properties of a conventional high speed design. The capping layer is made of compacted granular material.

ii. The transition zone with mat 2: this zone provides the transition of geometry for the substructure between ballasted track and slab track as displayed in Figure 1. The thickness of the ballast layer is progressively reduced in order to match the slab track layer profile. In the substructure the compacted granular material layer is replaced by cement bound granular material, designed to support the slab in the ballastless zone. Between ballast and subgrade a polyurethane mat is introduced to provide the stiffness transition between slab track and ballasted track.

iii. The transition zone with mat 1: this zone has the same characteristics as the first part of the transition, except that the mat is softer.

iv. The slab track: its design is adapted from the STEDEF layout for tunnel. A soft resilient pad is introduced between the sleepers and the slab and protected by a rigid shell. The slab is made in reinforced concrete and cast *in-situ*. The subgrade layer is the same as in the transition zone.

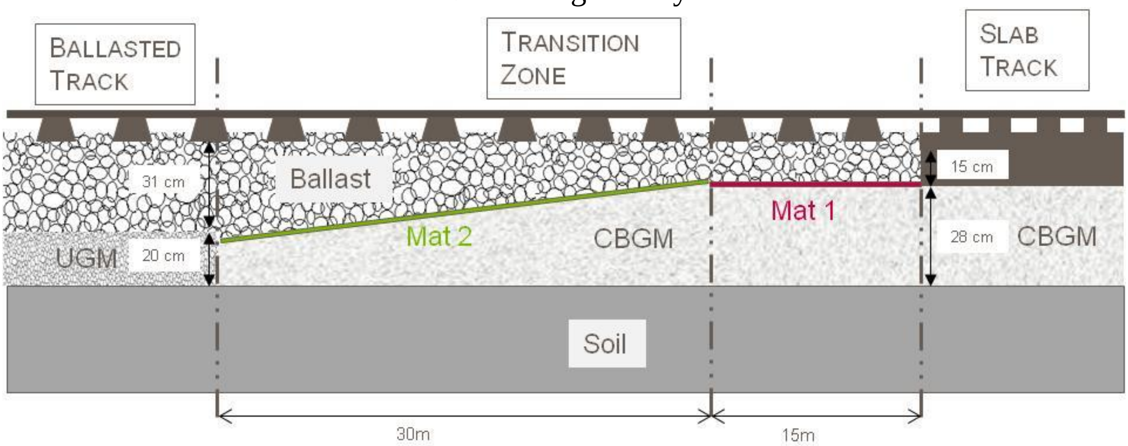


Figure 1: Description of track geometry in Chauconin test site (Costa d'Aguiar et al. 2015)

Experimental device

| | Brand | Type |
|---|---|---|
| Data acquisition software | Brüel&Kjaer | PULSE Labshop v17 |
| Data acquisition hardware | Brüel&Kjaer | LAN-Xi |
| Accelerometers | Brüel&Kjaer | 4513 |
| | DJB | A/120/V |
| Impact hammer | Brüel&Kjaer | 8050 |

Table 1: Measurement chain properties

A set of measurements is performed on each one of these zones. 8 sensors are used, 3 on sleepers and 5 on the top of the rail. The measuring equipment is described in Table 1. The experimental device is visible in Figure 2. Three points of impact are chosen, both on and between sleepers. A minimum of ten hammer impacts are performed at each chosen point, and the coherence is checked in real time (if it is below 0.9, the impact is rejected and another one is performed). An example of the load impact on rail and the corresponding acceleration in the time domain is presented in Figure 3.

Figure 2: Experimental device for receptance test in Chauconin

Transfer functions are evaluated following this equation:

$$H_{uF}(f) = \frac{S_{uF}(f)}{S_{FF}(f)}$$

with:
- f, the frequencies at which the different spectra are sampled;
- $H_{uF}$, the transfer function between signals u of displacement and F of force;
- $S_{uF}$, cross spectrum of signals u and F;
- $S_{FF}$, autopectrum of signal F.

The sampling frequency is 4096 Hz and the frequency step is 0.5 Hz.

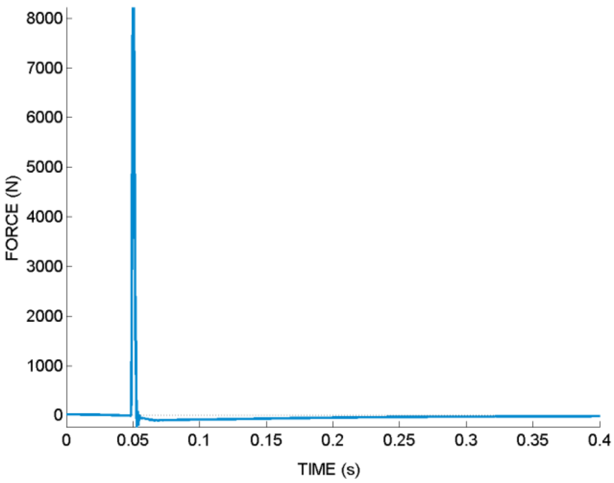


Figure 3a: Impact force time signal

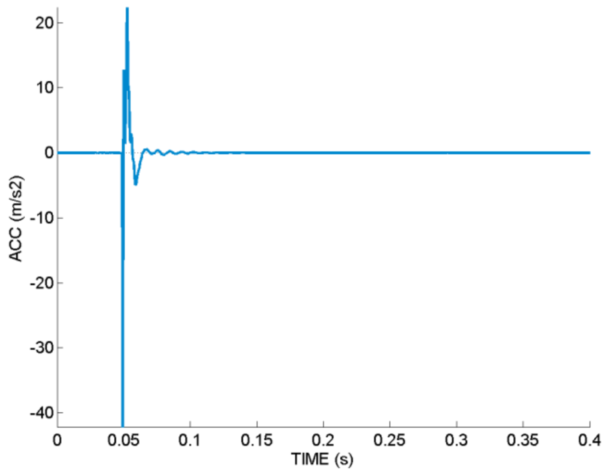


Figure 3b: Acceleration on rail time signal

RESULTS OF THE RECEPTANCE TEST

The results of experiments carried on the different zones are displayed in Figure 4 using a rectangular window. The curves presented in Figure 4 are an average over the ten hammer impacts at the same point for the direct receptance (the point where the displacement is measured is the same as the point of loading). Only the zones with a ballast layer are compared here: the slab track has a different superstructure and the explanation of its behaviour is beyond the scope of this paper.

The changes in the substructure are clearly visible in the curve shapes: zones of ballasted track with mats present softer response at low frequencies than zones with no mats. On the contrary, for frequencies higher than 40Hz, zones with mats are stiffer.

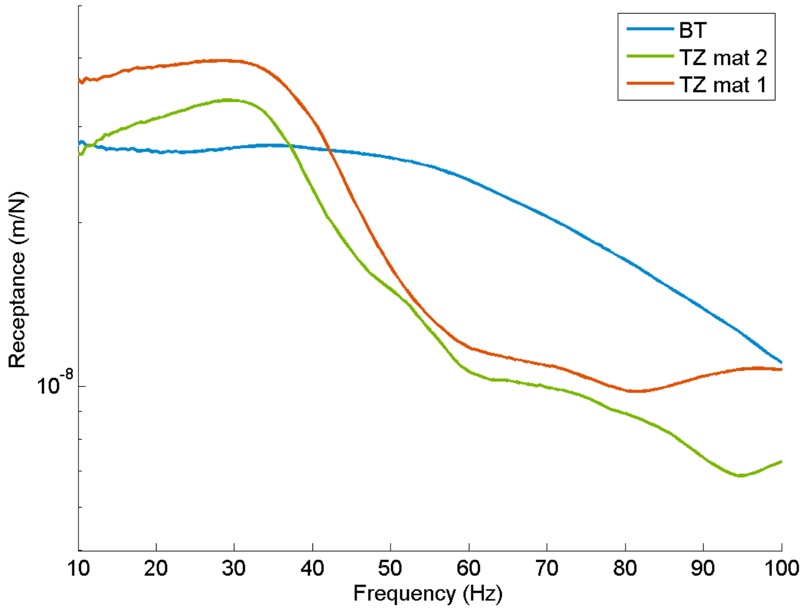


Figure 4: Receptance measurements

This difference is only due to the substructure as the superstructure in the two zones is strictly the same.

The key conclusion that can be drawn from Figure 4 is that receptance is efficient to diagnose a change in the substructure of the track. This test can then be seen as a non-intrusive tool to detect these changes. This statement is reinforced with Figure 5 that shows receptance measurements directly at the point of change from ballasted track to transition zone.

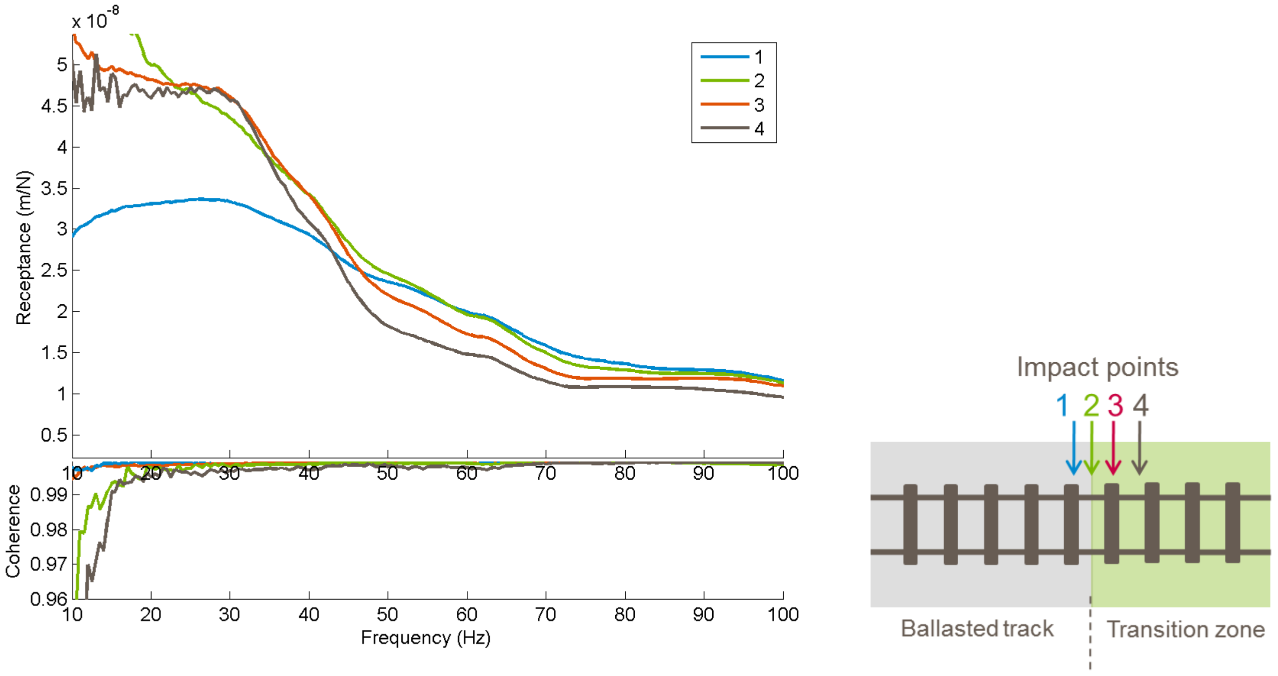


Figure 5: Receptance measurement at the transition between ballasted track and transition zone.

## NUMERICAL MODEL

### Description

Dynavoie software is a 3D finite element model using the periodicity of the track to reduce the size of the problem. Both frequency domain and time domain calculation are available.

The method is based on the finite element representation of a "slice": a basic cell with one sleeper repeated to form the track as displayed in Figure 6. The methodology in the frequency domain is based on Floquet transform and is described in the paper (Arlaud et al. 2015). For time domain calculation the track periodicity is used to reduce the number of degrees of freedom to take into account. First, an eigen mode calculation in the slice with periodic boundaries is performed, to construct a reduction basis. Super-elements (Qu 2004) are then created and separated into principal and interface ones (potentially different slices can be considered and aggregated). Then the track is generated in 3D using these super-elements instead of finite elements. This methodology allows to reduce the number of degrees of freedom (DOF) taken into account, which implies a reduction of both storage capacity required and time calculation.

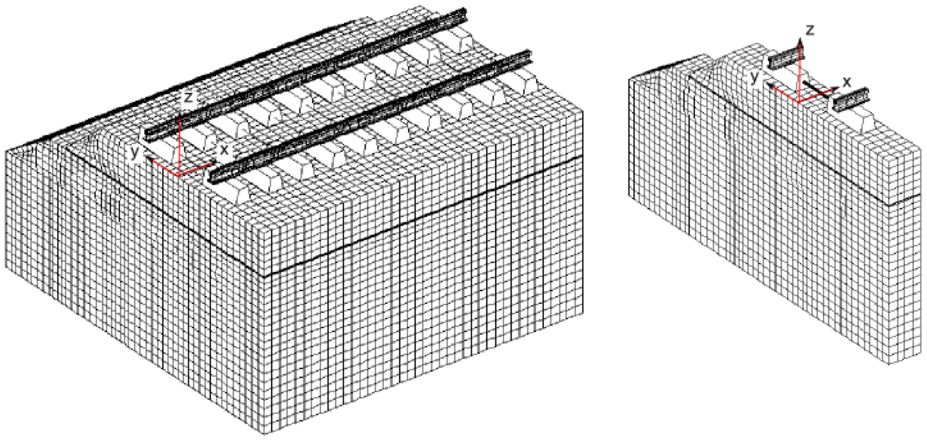


Figure 6: Representation of slice of the track

Two zones are represented using this model: the ballasted track and the adjacent part of the transition zone. The properties chosen for both sections are summarised in Figure 7 for geometry and in Table 2 and 3 for material properties.

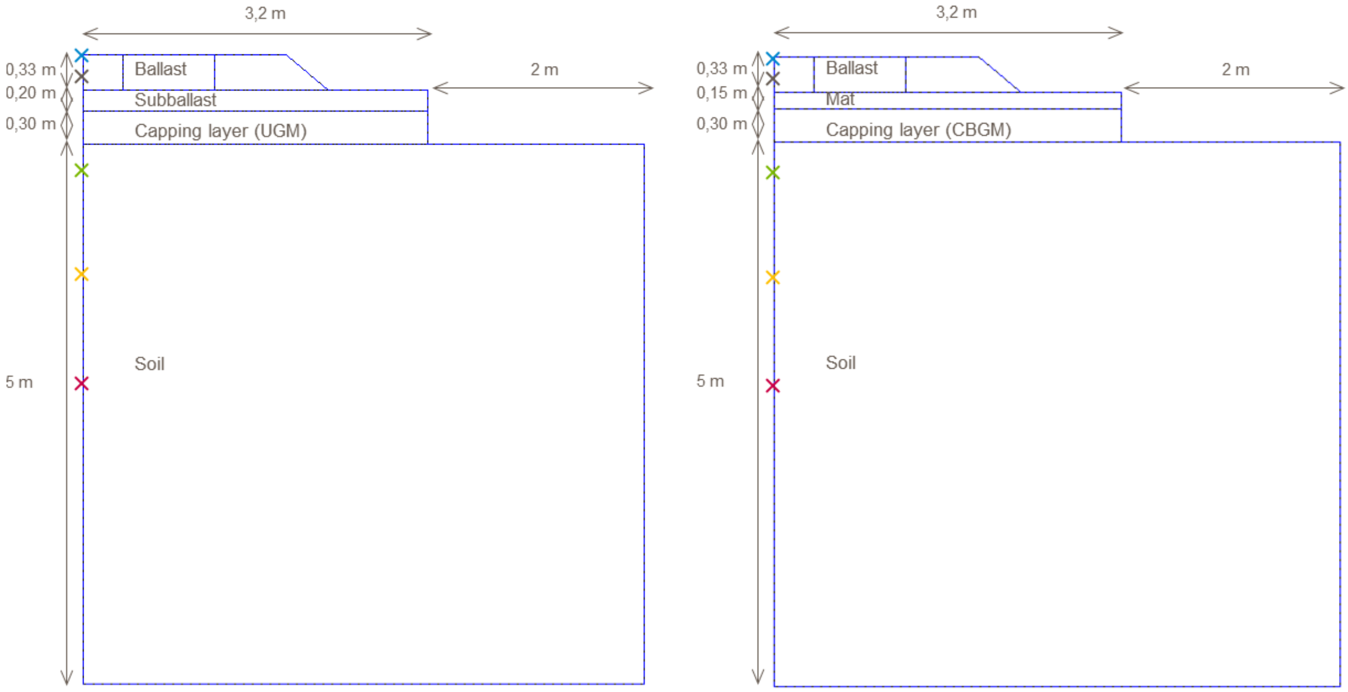


Figure 7: Geometric properties used in the model: on the left for ballasted track, on the right for transition zone

| | E (Mpa) | ν | ρ (kg/m$^3$) | ξ |
|---|---|---|---|---|
| Ballast | 200 | 0.3 | 1700 | 0.07 |
| Subballast | 180 | 0.3 | 2135 | 0.04 |
| Capping layer | 200 | 0.3 | 1800 | 0.04 |

Table 2: Material properties in ballasted track

| | E (Mpa) | ν | ρ (kg/m$^3$) | ξ |
|---|---|---|---|---|
| Ballast | 200 | 0.3 | 1700 | 0.07 |
| Mat | 0.25 | 0.3 | 900 | 0.07 |
| Capping layer | 23000 | 0.3 | 2000 | 0.04 |

Table 3: Material properties in transition zone

In both cases, the soil layer is modelled using the following gradient property rule for the Young modulus with a target modulus of 80 MPa at 1m depth in soil, and n=0.5:

$$E = E_0 \left( \frac{P_{\sup}}{P_0} \right)^n$$

More detailed on this choice can be found in the following paper (Arlaud et al. 2014).

Results in the frequency domain

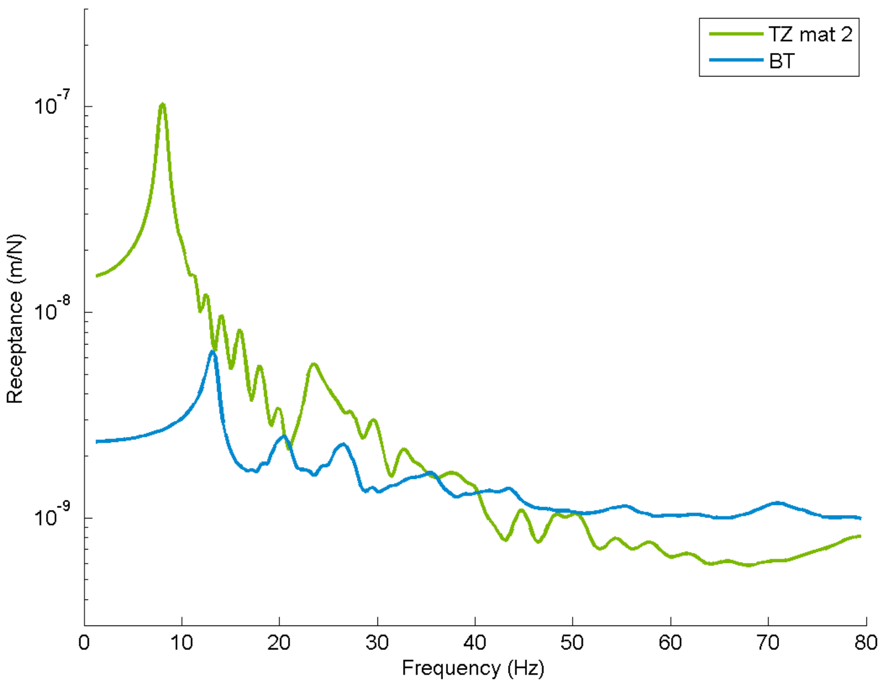


Figure 8: Numerical result for ballasted track and transition zone in Chauconin

Receptance curves can be computed using Dynavoie in the frequency domain. The comparison between ballasted track and transition zone with mat is proposed in Figure 8. The change in the substructure properties is clearly visible, as it was for experimental measurements. As in measured receptance curves, the structure with mat is softer below 40Hz than the structure without mats, and becomes stiffer above this frequency.

Generally, the same effects are then visible even if the parameters are set only with construction specifications and not optimized to match the receptance curves as it is sometimes done to calibrate models (Alves Costa et al. 2012; Alves Ribeiro et al. 2014). However, the curves are not yet exactly similar to the experimental ones; this is due mainly to the boundary conditions which are not yet adapted and to the wavenumber discretization.

The displacements corresponding to the main peak of the frequency response, identified at 8 Hz for the transition zone and at 11 Hz for the ballasted track are displayed in Figure 9.

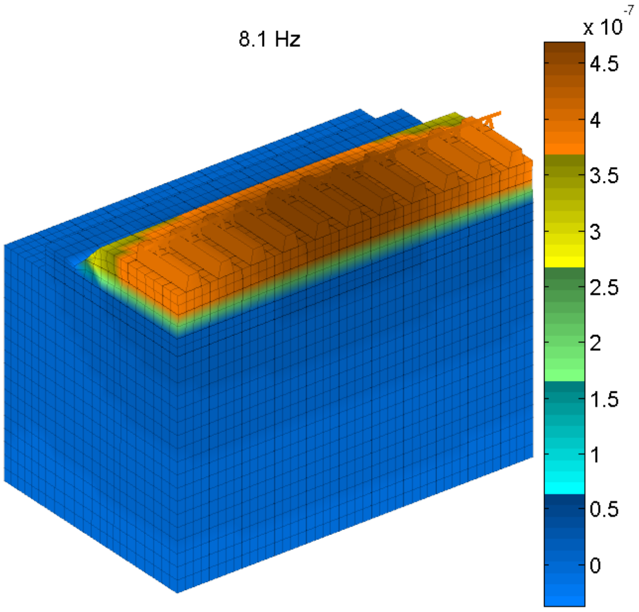


Figure 9a: Deflection at the main resonance peak of receptance curve for zone with mat 2.

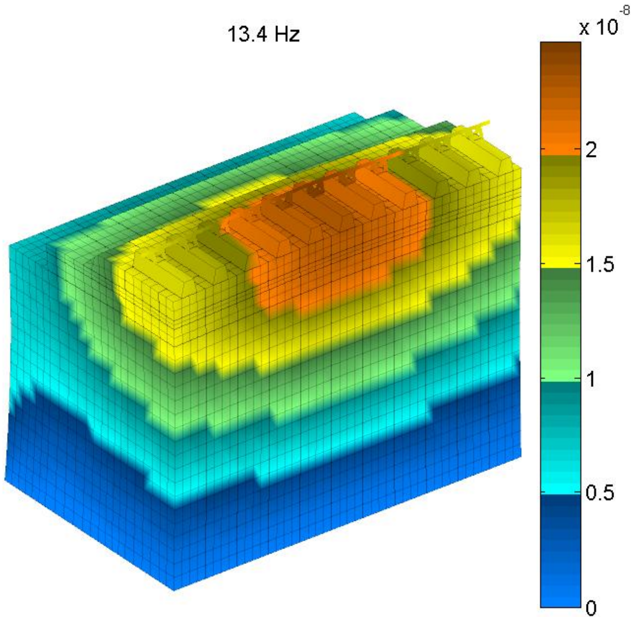


Figure 9b: Deflection at the main resonance peak of receptance curve for zone of ballasted track

The repartition of displacement in the layers is very different from one structure to another. Figure 9a shows that for the structure with mat there is almost no displacement in the substructure layer, whereas in the ballasted track displayed in Figure 9b the displacement reduction with depth is more progressive.
In the transition zone, vertical movement is concentrated in the upper layer (that is to say in the ballast layer). Energy is then confined in this part of the track, blocked by the combination of the very soft mat and the stiff capping layer underneath. Energy has to be dissipated in this layer and not in the whole substructure: this statement can explain the faster degradation of ballast particles in the transition zone than in the ballasted zone. The difference of this degradation rate is qualitatively illustrated by Figure 10, and is detailed in the (Costa d'Aguiar et al. 2015) paper. Abrasion of ballast particles is clearly more intense in the transition zone due to the different substructure.

Figure 10: Ballast particles of Chauconin zone. Left particle is from transition zone, right particle is from current ballast track

Results in the time domain

To verify the difference in displacement repartition with depth between the two structures identified in the frequency domain, a time domain computation is performed for the two structures presented above. The load case is a moving load of 8.7 t at a speed of 300 km/h. Figure 11 presents the results for the ballasted track and Figure 12 the results for the transition zone. The left part of the figures shows the repartition of displacement in layers. The curves on the right are the displacement, in time, at different depth filtered at

100 Hz. Measurement points are materialised in Figure 7 by coloured crosses. As stated in the frequency domain, the repartition of displacement with depth is very different from one structure to another, and is very similar to the one of the main peak of receptance response in the frequency domain displayed in Figure 9.

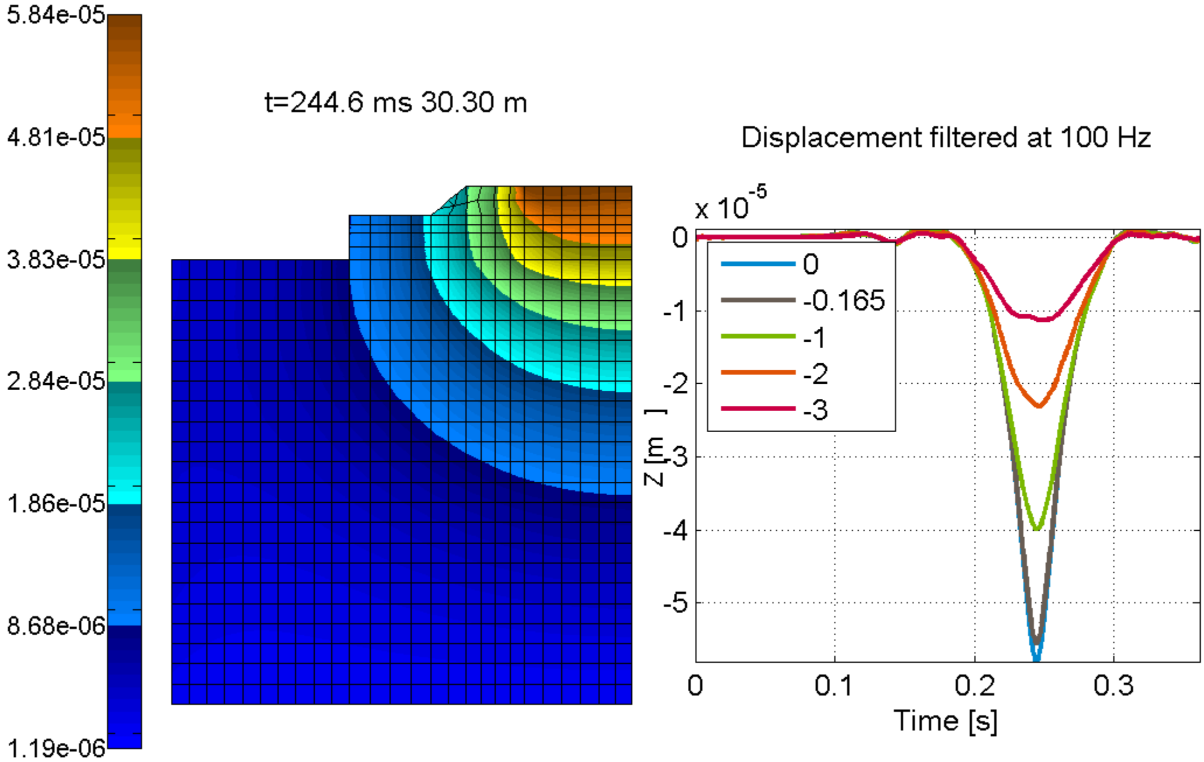


Figure 11: Displacement in the ballasted track

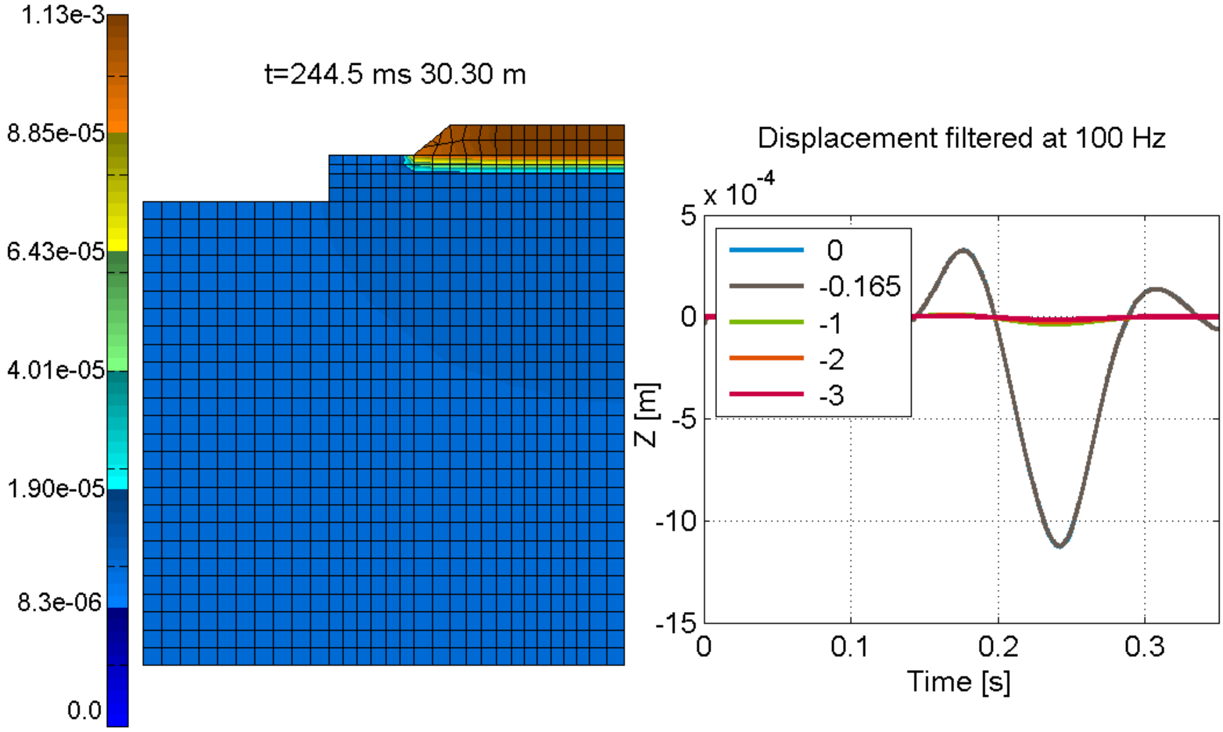


Figure 12: Displacement in the structure with mat

The main conclusion that can be drawn from these results is that the displacement corresponding to the main peak of the receptance curve is a good indicator of the track displacement under moving load. Frequency domain analysis of the track can then give clues on how the track will behave at passing trains in the time domain. The relation between both will be studied in detail in further research.

## CONCLUSIONS

Experimental tests have been performed in a transition zone presenting four different structures. The purpose of this test was to prove that a change in the substructure is clearly visible in the global response of the track characterized by the receptance test. This property has been verified with this experiment, and other measurements will follow, particularly in zones of bituminous layers.

Then receptance has been computed with an efficient numerical model. The differences linked to changes in the substructure are also clearly visible. The displacements corresponding to the maximal amplitude have been displayed using this model. The comparison of the response in the different zones is very useful to understand and explain the global differences. Indeed, the distribution of the displacement in the layers is very different from one structure to another. The model can thus be used to diagnose existing tracks and provide an explanation on the behaviour of track designs. This model also allows time response computations; the link between both will be deepened in further work.

## REFERENCES


Alves Costa, P., Calçada, R. & Silva Cardoso, A., 2012. Ballast mats for the reduction of railway traffic vibrations. Numerical study. *Soil Dynamics and Earthquake Engineering*, 42, pp.137–150. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0267726112001431.

Alves Ribeiro, C. et al., 2014. Under sleeper pads in transition zones at railway underpasses: numerical modelling and experimental validation. *Structure and Infrastructure Engineering*, pp.1–18. Available at: http://www.tandfonline.com/doi/abs/10.1080/15732479.2014.970203#.VOSn5vmG_BY.

Arlaud, E., Aguiar, S.C.D. & Balmes, E., 2015. Validation of a reduced model of railway track allowing long 3D dynamic calculation of train-track interaction. *Computer Methods and Recent Advances in Geomechanics*, pp.1193–1198.

Arlaud, É., Aguiar, S.C.D. & Balmes, É., 2014. A reduced track model to understand the dynamic behavior of the track. In *Georail International Symposium*. pp. 17–26.

Chebli, H., Clouteau, D. & Schmitt, L., 2008. Dynamic response of high-speed ballasted railway tracks: 3D periodic model and in situ measurements. *Soil Dynamics and Earthquake Engineering*, 28(2), pp.118–131. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0267726107000656.

Connolly, D.P. et al., 2014. Benchmarking railway vibrations – Track, vehicle, ground and building effects. *Construction and Building Materials*. Available at: http://www.sciencedirect.com/science/article/pii/S0950061814007661.

Costa d'Aguiar, S. et al., 2015. Railway Transitional Zones: A case History from Ballasted to Ballastless Track. *International Journal of Railway Technology*, 2(3).

Ferreira, P.A. & López-Pita, A., 2015. Numerical modelling of high speed train/track system for the reduction of vibration levels and maintenance needs of railway tracks. *Construction and Building Materials*, 79, pp.14–21. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0950061815000124 [Accessed January 20, 2015].

François, S. et al., 2010. A 2.5D coupled FE–BE methodology for the dynamic interaction between longitudinally invariant structures and a layered halfspace. *Computer Methods in Applied Mechanics and Engineering*, 199(23-24), pp.1536–1548. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0045782510000022.

Hall, L., 2003. Simulations and analyses of train-induced ground vibrations in finite element models. *Soil Dynamics and Earthquake Engineering*, 23(5), pp.403–413. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0267726102002099.

Knothe, K. & Wu, Y., 1998. Receptance behaviour of railway track and subgrade. *Archive of Applied Mechanics (Ingenieur Archiv)*, 68(7-8), pp.457–470. Available at: http://link.springer.com/10.1007/s004190050179.

Kouroussis, G., Verlinden, O. & Conti, C., 2011. Free field vibrations caused by high-speed lines: Measurement and time domain simulation. *Soil Dynamics and Earthquake Engineering*, 31(4), pp.692–707. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0267726110002769.

De Man, A.P., 2002. *DYNATRACK: A survey of dynamic railway track properties and their quality*.

Oregui, M., Li, Z. & Dollevoet, R., 2014. An investigation into the modeling of railway fastening. *International Journal of Mechanical Sciences*. Available at: http://www.sciencedirect.com/science/article/pii/S0020740314003932.

Qu, Z., 2004. Model Order Reduction Techniques with Applications in Finite Element Analysis: With Applications in Finite Element Analysis. Available at: https://books.google.fr/books?hl=fr&lr=&id=Uo7wVEbbg2IC&oi=fnd&pg=PA1&dq=Model+Order+Reduction+Techniques:+with+Applications+in+Finite+Element+Analysis&ots=IqpY6yrE9r&sig=vN5mFM3N2ArErB91dRw-Sq8P3Xk.

Thach, P.N., Liu, H.L. & Kong, G.Q., 2013. Vibration analysis of pile-supported embankments under high-speed train passage. *Soil Dynamics and Earthquake Engineering*, 55, pp.92–99. Available at: http://dx.doi.org/10.1016/j.soildyn.2013.09.006.

Yang, Y.B., Hung, H.H. & Chang, D.W., 2003. Train-induced wave propagation in layered soils using finite/infinite element simulation. *Soil Dynamics and Earthquake Engineering*, 23(4), pp.263–278. Available at: http://www.sciencedirect.com/science/article/pii/S0267726103000034.