Transportation Geotechnics 9 (2016) 1–16

Contents lists available at ScienceDirect

Transportation Geotechnics

journal homepage: www.elsevier.com/locate/trgeo

Receptance of railway tracks at low frequency: Numerical and experimental approaches

E. Arlaud [a,c,*], S. Costa D'Aguiar [b], E. Balmes [c,d]

[a] SNCF Reseau, Ingénierie & Projets, 6 Avenue François Mitterrand, 93574 La Plaine Saint Denis Cedex, France
[b] SNCF, Innovation & Research, 40 avenue des Terroirs de France, 75611 Paris Cedex 12, France
[c] Arts et Métiers ParisTech, PIMM, CNRS UMR 8006, boulevard de l'hôpital, 75013 Paris, France
[d] SDTools, 44 Rue Vergniaud, 75013 Paris, France

ARTICLE INFO

Article history:
Received 18 May 2016
Revised 22 June 2016
Accepted 23 June 2016
Available online 1 July 2016

Keywords:
Railway track
Dynamic
Modeling
Receptance

ABSTRACT

This paper presents numerical simulations and experimental studies on the frequency domain behavior of railway track below 100 Hz, focusing on the link between the substructure properties of the track and its global dynamic response. A numerical method in the frequency domain is first proposed and used to understand the frequency response of a railway track with a French High Speed Line (HSL) design. Then, low-frequency receptance measurements, performed in a specific HSL test site with different designs, are presented. These experimental results are used to characterize a change in the track substructure. Further analysis of the full track responses associated with peaks visible in the receptance test is conducted using numerical simulations. In the considered test case, these simulations demonstrate the existence of the superstructure and ballast resonance on relatively soft mats.

Introduction

The structure of railway tracks has changed little over years, and the few evolutions have been justified mainly on empirical bases. For instance, an experimental area of railway track over bituminous layer has been first built in the East European High Speed Line (HSL) in 2007 on 2 km, and the favorable feedback pushed for generalization of bituminous layers in new French HSL currently under construction. However, railway tracks are costly to construct (according to Campos and deRus (2009), the average cost for high speed line construction is 17.5 k€/m of track and 19 €/m for annual maintenance). This motivates studies on new designs reducing the need for maintenance. In order to face this challenge, railway infrastructure managers are willing to revise specifications related to track design in order to increase the life span of their infrastructures. Introduction of under sleeper pads, of ballast mats, or improvement of bearing soil capabilities are possible solutions to do so (Esveld, 1997). Assessing the mechanical performance of these new designs from the dynamic point of view is then required.

Experimentally, a widespread practical approach to get dynamic information on the global track behavior is to perform a receptance test. That is to measure the transfer from force on rail to the associated displacement, usually through a hammer test. This test characterizes the global behavior of track for a range of frequencies and allows the identification of the main resonances of the structure: it characterizes the structure sensitivity to vibrations (Man, 2002) and the dynamic flexibility of the track (Knothe and Wu, 1998). This test is not sufficient to give full information on track dynamic behavior under passing

* Corresponding author at: SNCF Reseau, Ingénierie & Projets, 6 Avenue François Mitterrand, 93574 La Plaine Saint Denis Cedex, France.

E-mail addresses: elodie.arlaud@sncf.fr (E. Arlaud), sofia.costada-guiar@sncf.fr (S. Costa D'Aguiar), balmes@sdtools.com (E. Balmes).

http://dx.doi.org/10.1016/j.trgeo.2016.06.003
2214-3912/

trains. To do so, the knowledge of the vehicle/track interaction and of the force acting on the track is also of valuable importance (Kouroussis et al., 2014), but receptance is a first quite easy experiment to get insight on track behavior. Although the results presented in this work will focus on the track substructure, it can be noted that receptance content can also be analyzed at higher frequencies, notably to adjust numerical model properties, as pad stiffness or spring characteristics for spring-dampers models of track (Kaewunruen and Remennikov, 2007; Ribeiro, 2012; Alves Costa et al., 2012; Verbraken et al., 2013) or to detect defects on rail (Oregui et al., 2015).

Coupled with the numerical model, receptance gives insights on the wave propagation in the substructure layers, as used by Berggren et al. (2010) to assess soft soil influence. The final objective of this work is to assess the track and platform dynamic behavior under passing trains. In that case, the characteristic lengths of the system generate excitations at frequencies that depend on train speed. These excitations are mainly below 100 Hz (not accounting for small rail defects and irregularities). This is the cutting frequency used to study receptance curve in this work.

Several numerical models have been proposed in the literature to represent track behavior. As Finite Element Models (FEM) are widely used for engineering purposes, various authors (Hall, 2003; Araújo, 2010; Kouroussis et al., 2011; Ju and Li, 2011; Banimahd and Woodward, 2007; Connolly et al., 2013; Connolly et al., 2014; Shahraki et al., 2015; Sayeed and Shahin, 2016), have represented tracks using 3D FE models. The two main drawbacks of these models are the large computational time and the large storage capabilities required: Ju and Li (2011) reported 9 days of calculation and a computer memory requirement of 6.5 GB for a model of 2 km of track with about 13 million degrees of freedom and 4000 time steps. Aiming at reducing time computation, authors have proposed 2D FE models with modified plane strain (Fernandes et al., 2014) or with modified plane stress condition (Ribeiro, 2012; Paixão et al., 2015), which allows good description of the track geometry but implies approximation regarding the cross section of the track. Even if the model is two dimensional, a track width can be specified to compute stress in layers. To calibrate its value, a 3D computation has to be made in parallel. This methodology leads to approximations since the repartition of stress is not uniform in the width of the track.

Considering the track as invariant in the rail direction, different authors have proposed a coupled Finite Element (FE)–Boundary Element (BE) numerical model in 2.5 D (Yang and Hung, 2001; Yang et al., 2003; François et al., 2010; Alves Costa et al., 2012). These approaches imply approximations on the track geometry since sleepers are discontinuous. As shown by Chebli et al. (2008), this limitation can be bypassed using Floquet transforms and computations on a generic 3D cell, considering track as periodic, as illustrated in Fig. 1. Computation time is then reduced and infinite soil layers can be considered.

Section '3D FEM with Floquet transform' details a methodology for the numerical computation in the frequency domain of 3D periodic models. This methodology is an alternative to Wave Finite Element method (Mace et al., 2005; Collet et al., 2011) used to compute wave propagation in wave guides. Links between the two approaches have been clarified in Balmes et al. (2016). In the field of railway modeling this approach is similar to the one of Chebli et al. (2008), based on the Floquet transform of a "slice" of the track. Outside a clarification of equations, the contribution of the section is a discussion of numerical strategies used to reduce models in the frequency domain and to choose wavenumbers for the spatial Fourier transform.

On a realistic track model, Section 'Numerical application' then uses the proposed methodology to detail the relation between peaks visible in receptance curves and propagating waves in the track.

The main drawback of existing wave domain approaches is that calculations can only be made in the frequency domain. The authors of the present paper have been long developing model reduction techniques for nominally periodic structures which use periodic solutions as starting vectors to build Ritz bases for the generic 3D cell. This concept has been used in Sternchüss (2009) for multi-stage rotors and since 2003 in the development of

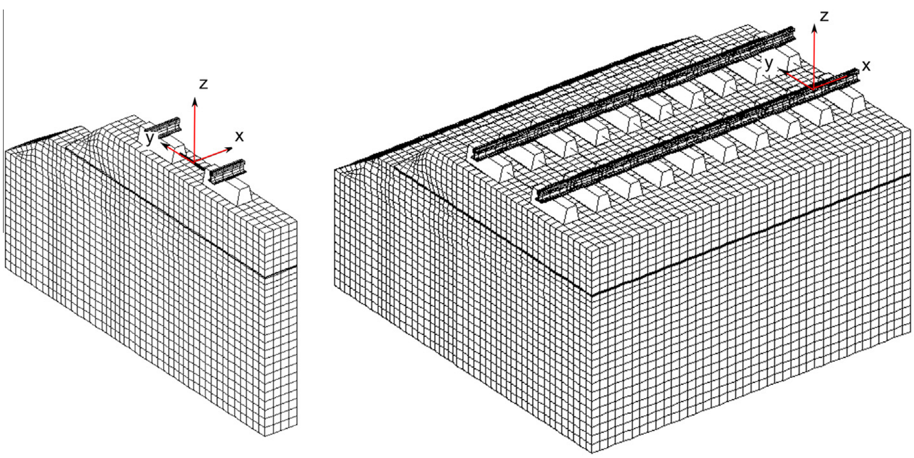

Fig. 1. Track as a periodic structure, the basic cell is on the left.