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The effect of railway local irregularities on ground vibration

Georges Kouroussis [a,*], David P. Connolly [b], Georgios Alexandrou [a], Konstantinos Vogiatzis [c]

[a] *University of Mons—UMONS, Faculty of Engineering, Department of Theoretical Mechanics, Dynamics and Vibrations, Place du Parc 20, B-7000 Mons, Belgium*
[b] *Heriot-Watt University, School of Energy, Geoscience, Infrastructure & Society, Edinburgh EH14 4AS, United Kingdom*
[c] *University of Thessaly, School of the Civil Engineering, Pedion Areos, 383 34 Volos, Greece*

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ABSTRACT

The environmental effects of ground-borne vibrations generated due to localised railway defects is a growing concern in urban areas. Frequency domain modelling approaches are well suited for predicting vibration levels on standard railway lines due to track periodicity. However, when considering individual, non-periodic, localised defects (e.g. a rail joint), frequency domain modelling becomes challenging. Therefore in this study, a previously validated, time domain, three-dimensional ground vibration prediction model is modified to analyse such defects. A range of different local (discontinuous) rail and wheel irregularity are mathematically modelled, including: rail joints, switches, crossings and wheel flats. Each is investigated using a sensitivity analysis, where defect size and vehicle speed is varied. To quantify the effect on railroad ground-borne vibration levels, a variety of exposure–response relationships are analysed, including: peak particle velocity, maximum weighted time-averaged velocity and weighted decibel velocity. It is shown that local irregularities cause a significant increase in vibration in comparison to a smooth track, and that the vibrations can propagate to greater distances from the line. Furthermore, the results show that step-down joints generate the highest levels of vibration, whereas wheel flats generate much lower levels. It is also found that defect size influences vibration levels, and larger defects cause greater vibration. Lastly, it is shown that for different defect types, train speed effects are complex, and may cause either an increase or decrease in vibration levels.

Introduction

Railway induced ground vibrations can cause negative effects on urban environments situated near rail lines. The propagation of railway vibrations (particularly in urban areas) is complex, due to the different transmission paths within a medium that is fundamentally inhomogeneous, non-engineered and infinite in three directions. There is a large body of research into railway-induced ground vibrations, such as their effect on urban environments and potential mitigation measures (e.g. wave impeding blocks (Coulier et al., 2013), trenches (Connolly et al., 2013a) or wave barrier (Garinei et al., 2014)). Furthermore, for high-speed trains (Degrande and Schillemans, 2001; Galvín and Domínguez, 2009; Costa et al., 2010; Connolly et al., 2015a), research is currently motivated by the so-called “supercritical phenomenon” which occurs when the vehicle speed is close to the Rayleigh ground wave speed. Critical speed depends on the soil flexibility and may be close

* Corresponding author.
E-mail address: georges.kouroussis@umons.ac.be (G. Kouroussis).

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to that of conventional high-speed lines (Madshus and Kaynia, 2000; Connolly et al., 2015b). Despite the large vibration levels generated by these lines which are underlain by soft soils (Connolly et al., 2014a), the distance d between the track and neighbouring structures is relatively high and the vibration attenuates rapidly. In the case of railway traffic, the attenuation is associated with a power law of the form d^{-q}, where q lies between 0.5 and 1.1, depending on the soil configuration (Auersch and Said, 2010). Connolly et al. (2014b) proposed that it is possible to establish relationships between six key railway variables for ground vibration metrics in the case of high-speed lines. The situation is significantly different for the case of urban transit, because:

- The distance d between track and building is relatively close.
- The contribution of the vehicle weight and speed (quasi-static effects) is low.
- The presence of local defects induces elevated localised vibrations (dynamic effects).

Local defects are a significant source of dynamic excitation on railway tracks. Accurate descriptions of the interaction between the track and the vehicle have been modelled by Nielsen and Abrahamsson (1992), Zhai and Sun (1994), Zhai et al. (2013), Oscarsson and Dahlberg (1998), and Andersson and Oscarsson (1999). They take into account the different elements of the track/foundation system. Similar research was also undertaken by Kouroussis et al. (2011) to show that an accurate simulation of track/soil interaction is important in the prediction of ground-borne vibration (Kouroussis and Verlinden, 2015). These numerical approaches offer the possibility of studying local defect effects on track dynamics. Indeed, the study of vehicle/track coupling with local defects is of growing interest. The influence of vehicle-flexible mode shapes on the ride quality has been investigated (Younesian et al., 2014), including singular geometrical imperfections. Mandal et al. (in press) propose simplified equations for the impact forces on wheels caused by permanently dipped rail joints; these elevated forces are characterised by high-frequency content in comparison to the typical static excitation, and occur for a very short duration. Uzzal et al. (in press) considered the dynamic impact response due to the presence of multiple wheel flats, for different sizes and relative positions of flat spots. Zhao et al. (2012) employed a three-dimensional finite element model to evaluate the wheel/rail impact forces at local rail surface defect zones. They also evaluated the resulting dynamic forces at the discrete supports of the rail under different train speeds. Grossoni et al. (2015) proposed a parametric study to understand the dynamic behaviour of a rail joint and the influence of track and vehicle parameters.

The aforementioned studies focus on the track/vehicle response however only a small number of studies have analysed the effect of local defects on ground vibration. Despite this, many ground-borne vibration complaints in urban environments are due to local rail and wheel surface defects (e.g. switches, rail joints, ...). Kouroussis et al. (2014c) quantified the vibration generated by a tram in the presence of a local rail defect using a numerical model in two successive steps. Using the same approach, Alexandrou et al. (in press) also studied the wheel flat effect on ground motion and analysed the influence of wheel flat size. In addition, Vogiatzis (2010, 2012) undertook a large-scale analysis of ground vibrations generated by underground Athens metro lines by studying wheel flat impact forces as impulses. Mitigations solutions were proposed by improving vehicle and track design, such as reduction in unsprung mass minimising wheel polygonalisation or wheel flat (Nielsen et al., 2015), creating transition zones to avoid abrupt changes in the track's vertical stiffness (Paixão et al., 2015) or lift-over crossings to minimise vibrations in sensitive buildings (Talbot, 2014).

As the source of vibration is the wheel/rail contact, it is essential to study vehicle interaction with the track and the soil. Therefore, Costa et al. (2012) showed the importance of integrating a multibody model of the vehicle with the track/soil simulations and that in the case of a distributed rail's unevenness, sprung masses have minimal effects on the ground vibration motion. Furthermore, Kouroussis et al. (2014a) concluded that the choice between a simple or detailed model for the vehicle depends upon the importance of wheel and rail unevenness. This is because transient vibration generated at rail or wheel discontinuities is not comparable to the continuous vibration due to wheel/rail roughness.

This paper analyses the effect of typical local rail and wheel surface defects as shown in Fig. 1. First, a general description of the prediction model, based on a numerical two-step approach, is presented. A validated (Kouroussis et al., in press) vehicle–track–soil model is studied, based on the AM96 trainset, largely used in Brussels Region (Belgium), for which substantial measured data exists (Kouroussis et al., 2013a). Different defect geometries and sizes are considered for various train speeds and then their effect on vibration levels analysed.

Classification of local defects

Fig. 2 shows the local rail and wheel surface defect geometries associated with the defects illustrated in Fig. 1. For each defect, the geometry and the shape "seen" by the wheel/rail interface are illustrated. The shape seen accounts for the wheel radius R_w and the vehicle speed v_0.

The link between these theoretical shapes (Fig. 2) and the physical defects that are present on track is not a one-to-one relationship. Instead, real defects may form a combination of the defects shown. Despite this, some typical cases can be considered: