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A combined numerical/experimental prediction method for urban railway vibration

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ABSTRACT

Railway-induced ground vibrations can cause negative effects to people/structures located in urban areas. One of the main sources of these vibrations is from the large vehicle forces generated when train wheels impact local defects (e.g. switches/crossings). The sole use of traditional in-field transfer-mobility approaches is well suited for plain-line assessments, however is more challenging when discontinuities are present, due to the generation of large magnitude impact forces. This paper presents a hybrid experimental-numerical approach that can predict ground-borne vibration levels in the presence of a variety of railroad artefacts such as transition zones, switches, crossings and rail joints on existing networks. Firstly, the experimental procedure is described, which consists of multiple single source transfer mobilities to determine the transmission characteristics between rail and nearby structures. This is then coupled with a combined multibody vehicle and track numerical model, which is capable of simulating vibration generation in the presence of railway discontinuities. The resulting model is advantageous over alternative approaches because it can account for complex railway discontinuities, while at the same time incorporating the large uncertainties associated with different soil configurations. It is used to analyse a case study, where it is shown that vibration levels are strongly dependent on vehicle speed, defect type and defect size.

1. Introduction

Ground-borne vibration is an undesirable form of pollution generated by railways and therefore a large amount of research has been done to evaluate the impact of railway lines on neighbouring structures. This has come in the form of both prediction and prevention. In the early stages of railway network design, vibrations are often evaluated using experiments [1,2] or empirical methods such as, for example, the calculation procedure proposed by Crispino and D'Apuzzo [3]. Some scoping calculation methods emerged recently and showed that it is possible to establish closed-form relationships between a few key railway variables for ground vibration metrics for free field situations [4] or considering soil-structure interaction [5]. In the case of railway traffic, the attenuation with distance d from the track is associated with a power law of the form d^{-q} where q lies between 0.5 and 1.3, depending on the soil configuration [6]. The situation is significantly different in the case of urban transit, due to the presence of local defects which induce elevated localised vibrations (dynamic effect — q being more important, close to 2 [7]). Regarding structural damage prevention, as explained by Connolly et al. [8], several actions are preferred at the railtrack structure (active mitigation, e.g. floating slab [9], rail suspension fasteners [10] or within the vehicle [11,12]), rather than the implementation of a more passive solution in the far-field (e.g. building isolators [13], reflectors [14], subgrade stiffening [15] or wave barriers [16]).

There are two main alternative approaches to evaluate vibration: numerical modelling and physical testing. Numerical modelling is suitable for performing parametric studies and for simulating situations where input parameters are well defined. However, for the case of urban railways, the uncertainties caused by complex topography and infrastructure arrangements (e.g. buried services) mean that it is often impractical. Therefore, in practise, physical testing is more commonly used and allows for the determination of transfer functions between a source (i.e. potential railway) and a receiver (i.e. existing building) [17]. Physical testing procedures are typically concerned with determining a line-source transfer mobility, which accounts for the contribution of a long length of train traversing a (relatively) smooth track. However, in urban environments, tracks are densely populated with

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localised rail discontinuities (e.g. rail joints, switches and turnouts), which generate vibration levels much larger than a horizontally continuous track.

Reviewing the body of research on railway-induced ground vibration, there are only a minimal number of studies analysing the effect of local defects. This is surprising given that many ground-borne vibration complaints in urban environments are due to local rail and wheel surface defects (e.g. switches, rail joints, ...). The first step in analysing this problem is to understand wheel/rail interaction at the defect location. In an attempt to do this, Zhao et al. [18] evaluated the wheel/rail impact forces at the location of local rail surface defect zones using a three-dimensional finite element model. They also evaluated the resulting dynamic forces at the discrete supports of the rail under different train speeds. Alternatively, Grossoni et al. [19] performed a parametric study to understand the dynamic behaviour of a rail joint and the influence of track and vehicle parameters on track dynamics. Mandal et al. [20] also studied the impact forces on wheels at dipped rail joints, showing that they were of very short duration, of high magnitude and with high-frequency content. The case of wheel flats and their effect on dynamic impact response has been studied by Uzzal et al. [21] and Alexandrou et al. [22], who both analysed the effect of multiple wheel flats and vehicle speed. Nielsen et al. [23] showed that no evident correlation with the speed was found when wheel flats are considered in ground vibration assessment.

In an alternative way, including ground vibration assessment, Vogiatzis [24] analysed ground vibrations generated in Athens in several locations due to underground metro lines by focusing on turnout locations only, considering that these locations are more critical in terms of annoyance. Xu et al. [25] studied the effect of the stiffness variations on dynamic train/turnout interaction and presented a method to optimise the design of railway turnouts. Talbot [26] presented a new type of crossing device, based on a re-designed switch, in order to fix high noise and vibration problems encountered in neighbour structures. Finally, Kouroussis et al. [7] showed that models based only on vertical wheel/rail forces fail to predict horizontal ground-borne vibrations generated by local rail joints. Kouroussis et al. further developed a multibody vehicle/track model to account for track discontinuities [27]. This model was capable of calculating the impact forces generated at a variety of rail joints or other localised defects with different dimensions.

The objective of this paper is to couple a newly developed discontinuity vibration prediction model with in-situ physical testing procedures. The final approach will be suitable for calculating the vibration response of any rail defect, for any case of existing railway line. First the physical testing procedure required to couple with the numerical model is described. Then the numerical model is presented, followed by a strategy to couple both physical and numerical models. Finally a case study is performed on a tram line and the effect of train speed and defect characteristics is investigated. The aim of the tool is to provide a method that improves the accuracy of railway vibration assessment while minimising costs.

2. Hybrid modelling approach

2.1. Overview

For ground vibration assessments on existing lines, in-situ monitoring is often used, however for new lines, either physical or numerical (or combined) approaches are more commonly used. Regarding numerical modelling, a variety of approaches have been proposed, including those for high-speed lines [28,29] and urban networks [30,31]. However, significant computation time is needed for a complete vehicle/track/soil simulation and a vast section of vehicle, track and soil parameters are necessary. Further, another shortcoming of this approach is the difficulty in determining track and soil parameters, thus introducing variability in ground vibration predictions [32]. Moreover, urban configuration information in dense cities (e.g. modified soil compositions due to human activities, drainage pipes, complex and coupled foundations, ...) is often unknown and thus difficult to take into account in prediction models.

Alternatively, in some situations, the use of physical experiments offers a rapid way to estimate the effect of such defects and to evaluate railway vibration levels. However, a drawback is that the true properties of the system are never determined. One solution to overcome the drawbacks of each approach is to combine field results with numerical data, as proposed by Verbraken et al. [33] or Auersch [34].

2.2. Physical modelling (vibration propagation)

Ground vibration near railway lines is caused by dynamic train loads, which are dependent upon the nature of the interaction between the railway vehicle and the track. As discussed by Kouroussis et al. [35], ground-borne vibrations generated by railroads can be categorised depending upon the excitation mechanism:

- If the track is characterized by a very high quality rolling surface, the effects generated by the moving of axle loads can be considered as static or quasi-static, thus affecting static track displacement (the term “quasi-static” is generally used where the vehicle's speed is significantly lower than the critical track and soil wave speeds).
- If surface imperfections play a role in wheel/rail force generation, then a dynamic excitation is added to the static contribution. In the case of low speeds (e.g. up to 80 km/h in an urban area), the dynamic excitation has a dominant influence on ground vibration levels.

In the case of a perfect track surface or where there are few irregularities along the track alignment, quasi-static effects dominate ground vibration. Due to the track invariance along the direction x, it is assumed that the effect of a moving wheelset j on a track/soil system can be represented by

$$f_{\text{exc},j} = \sum_{k=1}^{\infty} f_k\, \delta(x - kL) \tag{1}$$

where f_k is the force acting through the k-th sleeper interface at each distance L (sleeper spacing). The resulting vibrations at different distances from the track result from the summation of the effects of each force f_k in the near-field (Fig. 1(a)) and are often called line source vibration. In practice, the forces acting on sleepers far from the receptor have a negligible influence on the resulting vibration level, so Eq. (1) becomes:

$$f_{\text{exc},j} \approx \sum_{k=1}^{m} f_k\, \delta(x - kL). \tag{2}$$

This effectively excludes the impact of forces outside a predefined distance range (recent numerical simulations show a 50–60 m track length provides satisfactory results [36], giving a practical value for the number of sleepers m to be considered).

In the case of a local defect, the ground vibration near railway lines is the result of the interaction of the railway vehicle and the track irregularity (Fig. 1(b)). In addition, if the vehicle speed is low (e.g. light transit vehicles, like trams or metros), typically this type of line will also have a relatively high density of singular rail surface defects. In this case, dynamic track deflection dominates the ground wave generation [35] meaning that it is reasonable to consider a single force acting on the wheel/rail defect contact point as the only contributor to railway vibration. Therefore,

$$f_{\text{exc},j} \approx f_{\text{wheel/rail}} \tag{3}$$

represents the force acting at the wheel/rail interface when a wheelset j is in contact with the local defect. Notice that the location of excitation

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