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The effects of ballast on the sound radiation from railway track

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ABSTRACT

In a conventional railway track, the rails are laid on sleepers, usually made of concrete, which are supported by a layer of coarse stones known as ballast. This paper focuses on quantifying the influence that the ballast has on the noise produced by the vibration of the track, particularly on the rail and sleeper radiation ratios. A one-fifth scale model of a railway track has been used to conduct acoustic and vibration measurements. This includes reduced-scale ballast that has been produced with stone sizes in the correct proportions. Two different scaling factors ($1:\sqrt{5}$ and 1:5) have been adopted for the stone sizes in an attempt to reproduce approximately the acoustic properties of full-scale ballast. It is shown that, although a scale factor of $1:\sqrt{5}$ gives a better scaling of the acoustic properties, the stones scaled at 1:5 also give acceptable results. The flow resistivity and porosity of this ballast sample have been measured. These have been used in a local reaction model based on the Johnson-Allard formulation to predict the ballast absorption, showing good agreement with measurements of the absorption coefficient. The effects of the presence of the ballast on the noise radiation from a reduced-scale steel rail and concrete sleeper have been investigated experimentally with the ballast located on a rigid foundation. Comparisons are made with the corresponding numerical predictions obtained by using the boundary element method, in which the ballast is represented by a surface impedance. Additionally the finite element method has been used in which the porous medium is considered as an equivalent fluid. From these results it is shown that the extended reaction model gives better agreement with the measurements. Finally, the effects of the ballast vibration on the sleeper radiation have also been investigated for a case of three sleepers embedded in ballast. The ballast vibration is shown to increase the sound radiation by between 1 and 4.5 dB for frequencies between 20 and 300 Hz at full scale whereas at higher frequencies the effect is negligible.

1. Introduction

In most situations, for conventional speeds, rolling noise is the dominant source of noise from the railway system. It is radiated by vibration of the wheels, the rails and, at low frequencies, the sleepers. Although the TWINS model [1] is widely used and has been extensively validated, less work has been done on the low frequency components of the noise. Moreover, the effects of ballast, such as its absorption properties, have been ignored up to now in the prediction of the sound radiation from the track.

Recently, the authors have developed improved models based on the boundary element method (BEM) for the sound

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radiation from rails in proximity to an absorptive ground and validated them against laboratory experiments [2]. In [3], improved models based on BEM for the sound radiation from sleepers have also been presented and validated through laboratory measurements. These included tests with an absorptive ground consisting of melamine foam. In reality, the sleepers are embedded in the ballast. It is necessary, therefore, to investigate the acoustic properties of ballast and its influence on the sound radiation from the rails and the sleepers.

The ballast is a layer of coarse stones supporting the sleepers. It supports the track vertically and provides lateral stability. In dynamic models of track behaviour, the ballast is usually represented as a series of springs and dampers beneath sleepers [4]. Ahlbeck et al. [5] conducted some theoretical work on the ballast vibration, assuming that the load was transmitted within a cone region in the ballast. Zhai et al. [6] proposed a five-parameter ballast vibration model based on the hypothesis that the transmission of the load from the sleepers to the ballast approximately coincides with a cone distribution.

From an acoustical point of view, the gaps between the stones make it behave as a porous material, absorbing noise to some extent. As early as 1940, the absorption coefficient of ballast was measured in a reverberation chamber by Kaye et al. [7]. More recently non-acoustic measurements were made of the flow resistivity, stone density and porosity of ballast by Attenborough et al. [8]. Using BEM predictions it was shown that the ballast absorption should reduce the A-weighted broadband sound pressure level radiated by the track. The ballast was considered as an extended reaction medium by Heutschi by using an electrical transmission line for the ballast [9]. The acoustic properties of railway ballast were also investigated recently by Broadbent et al. [10] in terms of the diffuse field absorption coefficient and the excess attenuation at a receiver for propagation over a layer of ballast.

It can be seen therefore, that during a train pass-by, the ballast can vibrate, leading to reradiated noise, while also absorbing the incident sound to a certain degree. It is not clear, however, to what extent these two effects contribute to the noise radiated to the side of the track and how much the mechanical and acoustical properties of the ballast modify the radiation from the rail and the sleeper.

This paper presents the results of measurements performed on a scale model of a railway track, focusing on the influence of the ballast absorption and vibration on the sound radiation from the rail and the sleeper. The geometrical scale of the model is chosen as 1:5. By using the same materials while reducing the geometrical dimensions by this scale factor, equivalent dynamic properties are obtained at frequencies that are 5 times higher than at full scale. Scale model steel rails have been obtained and concrete sleepers have been constructed, which have also been used in [2,3]. For the ballast the scaling presents additional difficulties. According to Junger [11], a correct acoustic scaling of a porous absorptive material requires that interstitial spaces are scaled according to $1:\sqrt{N}$ while the overall geometry should be scaled by $1:N$, where N is the chosen scale factor. Thus in the case of ballast this approach would require stones scaled by $1:\sqrt{5}$ arranged in a layer of ballast with a depth scaled by 1:5. In contrast, the overall mechanical properties of the ballast (apart from the gravity loading) would be correctly reproduced by maintaining the 1:5 scale factor for the sieved ballast stones as well as the layer thickness. Thus, there are two approaches to scaling the ballast; the first should give correct acoustic behaviour, i.e. absorption, while the second should give correct mechanical behaviour, i.e. vibration. For both of these scaling approaches, reduced scale ballast with a suitable range of stone sizes has been produced by sieving granite railway ballast with a range of appropriately sized sieves. To assess the effect of the scaling of the material, the absorption coefficient for both $1:\sqrt{5}$ and 1:5 stone sizes is considered in Section 2. The flow resistivity and porosity of the ballast with 1:5 stone sizes are also measured. In all cases the geometry of the ballast layer is scaled by for factor 1:5 and so the frequency is scaled by a factor of 5. A local reaction model is then used to determine the ballast absorption based on the measured flow resistivity and porosity. The effects of the ballast absorption on the sound radiation from the rail and the sleeper are quantified by measurements in terms of the radiation ratio in Section 3. These are compared with numerical predictions obtained by using the boundary element method, in which the ballast is represented by a surface impedance. In addition, the finite element method is used in which the porous medium is considered as an equivalent fluid. The effects of ballast vibration are considered in Section 4. For the sleeper embedded in ballast, the ballast vibration per unit force is measured by means of a scanning laser vibrometer. Finally, the effects of the ballast vibration on the sleeper radiation are estimated by means of a prediction based on the Rayleigh integral. Throughout the paper, results are presented at the frequencies corresponding to the scale model so that the corresponding frequencies at full scale are five times lower.

2. Acoustic properties of railway ballast

As a porous material, the ballast has absorptive properties that will have an influence on the rail and sleeper radiation. Before investigating the acoustic behaviour of the ballast, it is first necessary to determine two important and fundamental quantities: its flow resistivity and porosity. Due to the difficulties of working with full scale ballast (typical stone sizes are 50 mm, so a representative sample would be quite large) measurements have been made here of the flow resistivity and porosity of samples of 1:5 scale ballast with the correct gradation [12] at reduced scale. A local reaction model is then used to model the absorption of the scale ballast.

2.1. Measurement of the flow resistivity of ballast

The flow resistivity of a porous material is the most important parameter in determining its surface impedance and