RAILWAY ROLLING NOISE MITIGATION THROUGH OPTIMAL TRACK DESIGN

V. T. Andrés*, J. Martínez-Casas, J. Carballeira, F. D. Denia and D. J. Thompson†

* Instituto de Ingeniería Mecánica y Biomecánica (I2MB)
Universitat Politècnica de València
Valencia, Spain
e-mail: vicanrui@etsid.upv.es, jomarc12@mcm.upv.es, jacarmo@mcm.upv.es, fdenia@mcm.upv.es

† Institute of Sound and Vibration Research (ISVR)
University of Southampton
Southampton, United Kingdom
e-mail: djt@isvr.soton.ac.uk

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Abstract: *The main goal of the present work lies in the identification of the railway track properties that influence acoustic radiation, as well as in the analysis of these properties for the reduction of sound levels. This is achieved through a dynamic model of the railway wheel and track that allows the study of rolling noise, produced as a result of the wheel/rail interaction. Once the vibrational response of the railway components is determined, the sound power radiated by them is evaluated. The influence of the track properties on the sound radiation is determined by analysing the acoustic power results of different track configurations. From the results obtained, a number of guidelines are presented for noise mitigation of the involved railway elements. Between the worst and the best track design, there are differences of approximately 7.4 dB(A) in the radiation considering the wheel, rail and sleeper noise.*

1 INTRODUCTION

Noise pollution due to transport is one of the most damaging environmental factors for humans, according to the World Health Organization [1]. The consequences of prolonged exposure to high noise levels include, in order of severity, hearing loss, hypertension, ischaemia, insomnia and even changes in the immune system [2]. Consequently, the development of tools for detection, analysis and mitigation of sound levels radiated from railway transport is of great importance. Among the sources of acoustic radiation of railway vehicles, rolling noise is considered one of the most relevant [3].

In this work, a dynamic model of the wheel and track is implemented, which allows calculating the rolling noise radiated by the different railway elements (wheel, rail and sleeper). With this approach, the geometric and viscoelastic parameters of the track that most influence sound radiation are identified. Also, the necessary changes in these factors to reduce railway noise levels are determined [4].

The vibroacoustic model and methodology for the analysis of track influence on sound radiation are presented in Section 2. Results of an optimal track design as well as some guidelines to achieve noise mitigation are given in Section 3. In Section 4 the conclusions of the work are summarised.

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2 METHODOLOGY

2.1 Vibroacoustic model

To model the dynamic behaviour of the wheel, the Finite Element Method (FEM) is applied. Vibration modes of the wheel can be characterized according to the number of nodal lines (no vibration) that cross the wheel in a radial direction passing through its centre, known as nodal diameters [5]. This characterization allows grouping the contribution of the modes to the motion of the wheel and, consequently, to its acoustic radiation. By adopting a modal approach, the vibrational response of the wheel is evaluated.

After solving the dynamics of the railway wheel, its acoustic radiation is calculated as a postprocess of the vibrational field on its surface. The radiation model used in this work was

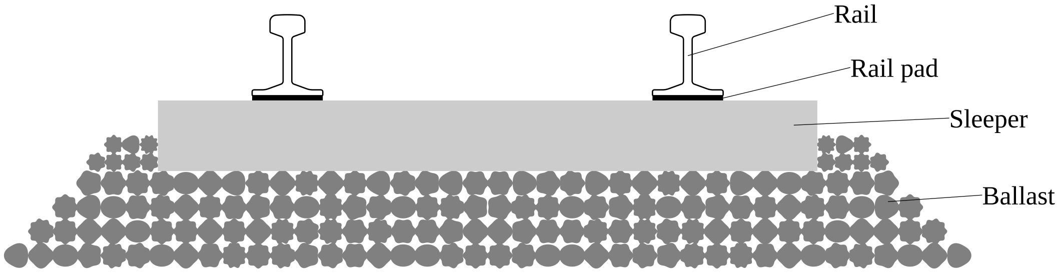

Figure 1: Railway track model configuration.

Due to the wheel/rail interaction force, structural waves propagate in the longitudinal direction through the infinite track. These propagating waves are evaluated applying the methodology proposed by Mead, whose formulation can be found in [9]. This consists of analysing a finite track segment using FE techniques. Using this approach, the displacement of any point on the track is obtained as a superposition of waves.

Regarding the sound radiation of the track, in this work it is assumed that there is a contribution from the rail and sleeper. The acoustic models of both components implemented in this work are described in [10] and it is assumed a two-dimensional radiation of each cross-section of the track, which is subsequently corrected to consider the three-dimensional nature of the sound radiation. Given the proportionality of the acoustic power and dynamic response of a component, the radiation from the rail and sleeper is also obtained as a superposition of the radiation associated with each wave.

The coupling between the wheel and track occurs through the wheel/rail interaction. The roughness present on the surfaces of both components is a source of excitation when the vehicle travels along the track. This excitation generates a vibrational field in the railway elements, producing rolling noise. A roughness spectrum defined in the standard EN13979-1 [11] is used. The contact model proposed by Thompson [12] is used in this work, which evaluates the interaction force from the wheel and rail combined roughness.

2.2 Influence analysis

This work aims to analyse the influence of the railway track design on the sound radiation of the wheel, the rail and the sleeper. In particular, the effect of the rail geometry and viscoelastic properties of the rail pad and ballast are studied. To do this, first, the rail profile is parameterised in six main variables (see Figure 2) and their limits are established; similarly, limits are set for the viscoelastic properties of the pad and ballast. Subsequently, a design of experiments and an ANOVA are carried out on the results, looking for a regression model that fits the calculated acoustic power. If the fit is good enough, the analysis of the regression coefficients allows knowing the influence of the different contributing variables on the sound radiation.

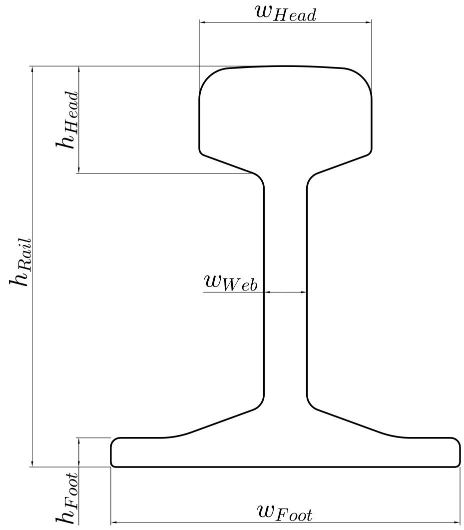

Figure 2: Rail profile parameterization.

In total, ten main parameters of the track are considered. Six of them describe the geometry of the rail (see Figure 2): w_{Head}, h_{Head}, w_{Foot}, h_{Foot}, w_{Web} and h_{Rail}; two represent the stiffness and damping of the rail pad, k_{Pad} and η_{Pad}, respectively; and the last two represent the stiffness and damping of the ballast, $k_{Ballast}$ and $\eta_{Ballast}$, respectively. In order to analyse the influence of these on sound radiation, a factorial design is proposed, covering all possible combinations of the variables. An ANOVA is performed on the result of the simulations, modifying the effects to ensure their statistical significance on radiation. The total acoustic power, which is the sum of the power of the rail, sleeper and wheel, is quantified by adding the energy contained in the frequency spectrum after including the A-weighting of the sound levels.

In this work both the influence of each parameter and its importance on the sound radiation are determined. For this, the technique developed by Pratt [13] is applied, by which the importance of each contributing variable is determined from the set of samples obtained from the factorial design calculation. For these samples, a polynomial regression is performed, given by:

$$\hat{\mathbf{y}} = \sum_j \beta_j \mathbf{x}_j, \tag{1}$$

where the response variable $\hat{\mathbf{y}}$ is the total radiation of each combination of the design of experiments previously standardised to unit variance and null mean, $\mathbf{x}_j$ is the standardised jth effect and β_j is the jth coefficient. An effect can be a simple parameter, an interaction or a power. Note that the vector of the adjusted response variable $\hat{\mathbf{y}}$ is obtained as a linear combination of the standardised effects $\mathbf{x}_j$, which form the basis of the vectorial subspace of the model. For two effects, this concept can be visualized in Figure 3.

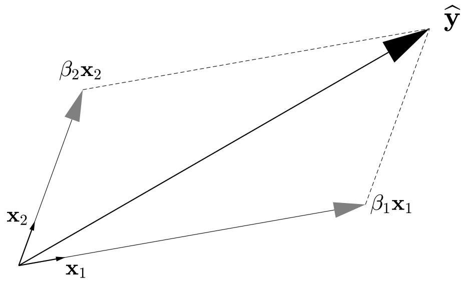

Figure 3: Vectorial subspace of the regression model.

The projection of $\beta_j\mathbf{x}_j$ onto $\hat{\mathbf{y}}$ represents the importance of the jth effect. In this work, the importance of the jth effect d_j is defined as follows:

$$d_j = \hat{\mathbf{y}} \cdot (\beta_j\mathbf{x}_j), \tag{2}$$

which represents the proportion of variance in the response variable that the jth effect explains. Consequently, the cumulative importance of all significant effects results in the coefficient of determination R^2 of the regression model.

3 RESULTS

The implemented vibroacoustic tool described in Section 2.1 has been verified with the commercial package TWINS [7, 8], which is considered as the reference program in railway rolling noise calculation.

To study the track influence on sound radiation, a design of experiments is carried out with five levels of each parameter. For each combination of them, the sound radiation of the railway components is calculated using the implemented tool. An ANOVA with the significant effects is performed on the results and the Pratt methodology, described in Section 2.2, is applied to determine the variability explanation of each effect. Using this technique, the variables influencing the total radiation are established, which are the width of the rail foot (w_{Foot}) and the four viscoelastic parameters of the track (k_{Pad}, η_{Pad}, $k_{Ballast}$ and $\eta_{Ballast}$). The polynomial regression model performed on the results of the factorial design has a coefficient of determination $R^2 = 99.43$ %. In Figure 4 the importance of each significant effect of the regression model as well as the cumulative importance are shown. The stiffness of the rail pad is the most important parameter, explaining 83.58 % of the sound radiation variability.

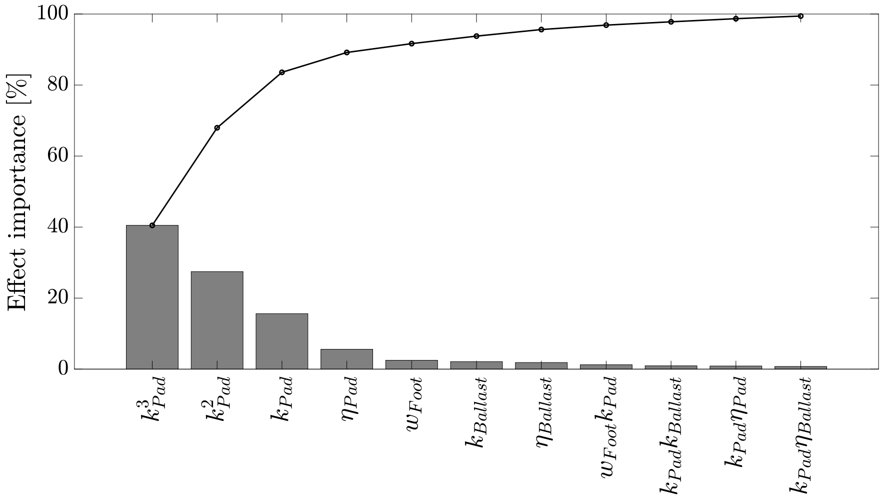

Figure 4: Importance and cumulative value of the significant effects.

An increase in the rail pad stiffness leads to a reduction in the rail and wheel noise and an increase in the sleeper radiation; for the total noise, at low stiffnesses the reduction of rail noise predominates and at high stiffnesses there is a balance between the three components. Regarding the rest of the parameters, a reduction in the rail foot width results in lower radiation levels of the rail as it reduces the radiation ratio and radiation area; the rail pad damping and ballast damping reduce the vibration amplitudes of the rail and sleeper, yielding a positive influence on their sound radiation; the ballast stiffness governs the vibrational response of the sleeper and, consequently, its acoustic power.

The optimal solution for the total sound power corresponds to a minimum value of w_{Foot} and maximum values of η_{Pad}, $k_{Ballast}$ and $\eta_{Ballast}$; regarding k_{Pad}, the minimum sound power levels are obtained with an intermediate/high stiffness, where the aforementioned balance is achieved. The regression model predicts that the optimal design is reached with the following parameters: $w_{Foot} = 120$ mm, $k_{Pad} = 780$ MN/m, $\eta_{Pad} = 0.5$, $k_{Ballast} = 100$ MN/m and $\eta_{Ballast} = 2$, with an acoustic power of 98.4 dB(A). In contrast, the worst design corresponds to the following parameters: $w_{Foot} = 150$ mm, $k_{Pad} = 130$ MN/m, $\eta_{Pad} = 0.25$, $k_{Ballast} = 40$ MN/m and $\eta_{Ballast} = 1$, with a power of 105.8 dB(A). Therefore, there is a difference between the best and the worst combination of 7.4 dB (A). Figure 5 shows the sound power levels of the track design with the worst combination of parameters and with the optimal combination.

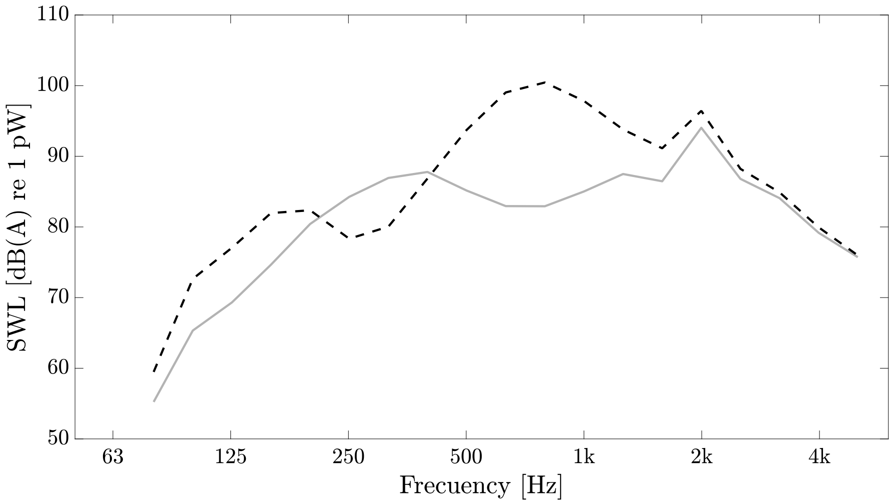

Figure 5: Sound power level for one wheel and associated track vibration. Best track design (——) and worst design (- - -).

4 CONCLUSIONS

A vibroacoustic model of the railway wheel and track has been implemented for the prediction of noise radiation from the wheel, rail and sleeper. A geometric parameterization of the rail profile has been carried out, which has allowed performing a design of experiments in order to analyse the influence of the track design on sound radiation. The geometry of the rail, represented by six variables, and the stiffness and damping of the rail pad and ballast, modelled through four additional variables, are studied.

The most important contributing variables are the viscoelastic properties of the rail pad and ballast and the width of the rail foot. The minimum sound power levels are found with minimum values of the rail foot width, maximum values of the rail pad and ballast damping, maximum values of the ballast stiffness and intermediate/high values of the rail pad stiffness. These values conform the optimal track design, which originates a total radiation 7.4 dB(A) lower than the worst track design found.

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