The Prediction of Vibration Transfer for Railway Induced Ground Vibration

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Summary. The project Railway Induced Vibration Abatement Solutions (RIVAS) is carried out under the EU's Seventh Framework Programme for Research and aims at reducing the environmental impact of ground-borne vibration from railway traffic.

Within the frame of the RIVAS project, an experimental procedure has been established to assess the efficiency of different mitigation measures for railway induced vibration. As an alternative to the experimental assessment, the performance of mitigation measures is often assessed relying on numerical simulations, which requires an accurate prediction of the vibration transfer. Benchmark tests are therefore carried out to investigate to what extent the vibration transfer can be predicted based on preliminary site investigation. In this paper, the results are presented for a site in El Realengo (Spain). First, the free field transfer functions are predicted based on a soil profile identified from geophysical tests. After updating of the material damping ratio, good prediction accuracy is obtained. Next, the track is included in the analysis. The track parameters strongly influence the track receptance and are therefore updated based on the measured track receptance under loaded conditions. The track – free field transfer functions are only slightly affected by the track parameters and are predicted accurately.

1 Introduction

The project Railway Induced Vibration Abatement Solutions (RIVAS) [1] is carried out under the EU's Seventh Framework Programme for Research and aims at reducing the environmental impact of ground-borne vibration from railway traffic. Within the frame of the RIVAS project, abatement measures for ground-borne noise and vibration for tracks at grade are studied. The aim is to develop innovative measures at the source to reduce the annoyance of lineside residents. Mitigation measures studied apply to rail vehicle design, rolling stock maintenance, track design, subgrade engineering, and the transmission path within the railway infrastructure.

In work package 1 of the RIVAS project, test procedures have been established to determine the performance of mitigation measures under realistic conditions where the performance of mitigation measures is determined experimentally by measuring the

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decrease in vibration transfer obtained after installation. The following procedure is used. Two sections with similar conditions are selected along the same railway track: a test section, where the mitigation measure is installed, and a reference section. An accurate experimental assessment of the mitigation measure requires the measurement of transfer functions at both sections, before and after installation, so that a correction can be made for the difference in vibration transfer between both sections, and the difference in vibration transfer between both measurement times.

As an alternative to the experimental assessment, the performance of mitigation measures is often assessed relying on numerical simulations, requiring an accurate prediction of the vibration transfer. Within the framework of the RIVAS project, benchmark tests have been carried out at a number of sites to investigate to what extent the vibration transfer can be predicted based on input data of the soil and input data for the track, both provided by preliminary site investigation. In this paper, the results are discussed for a site in El Realengo (Spain).

2 Free Field Transfer Functions

2.1 Description of the Site

The site in El Realengo is located in the Segura river flood plain next to the railway line between Murcia and Alicante, where a new high-speed railway is under construction. At this site, the effectiveness of subgrade stiffening next to the track as a mitigation measure will be assessed. Thus, a test section is selected adjacent to the existing conventional line where the mitigation measure will be installed together with a reference section along the same track with no mitigation.

The soil at the site in El Realengo consists of a desiccated upper crust, soft flood plain soil layers and hard alluvial cone soil layers on top of triassic bedrock. The dynamic soil properties have been evaluated by geophysical tests performed by CEDEX in April 2012, including Spectral Analysis of Surface Waves tests, seismic piezocone down-hole tests and seismic refraction tests, both at the test site and the reference site. The identified layer thickness, shear wave velocity, dilatational wave velocity and density for each layer of a horizontally layered soil profile are summarized in Table 1. The estimated material damping ratio is subsequently determined more accurately based on the measured free field transfer functions.

Table 1. Dynamic soil properties at the site in El Realengo (provisional values indicated by *)

Layer	h [m]	C_s [m/s]	C_p [m/s]	β_s [-]	β_p [-]	ρ [kg/m^3]
1	0.30	270	560	0.025*	0.025*	1800
2	1.20	150	470	0.025*	0.025*	1750
3	8.50	150	1560	0.025*	0.025*	1750
4	10.00	475	1560	0.025*	0.025*	1900
5	∞	550	2030	0.025*	0.025*	1900

2.2 Experimental Results

The free field transfer functions are measured both at the reference section and the test section by means of a falling weight deflectometer. Impacts are applied on a circular metallic foundation installed at 12 m from the centerline of the track while the ground velocity is measured using geophones installed on a straight measurement line perpendicular to the centerline of the track at a distance of 2 m to 64 m from the source.

The transfer function between the applied impact and the measured velocity is determined based on a number of impacts in order to improve the signal-to-noise ratio. The measured transfer functions and the 95 % confidence interval are shown in Fig. 1 for both sections at 6 m, 12 m, 24 m and 48 m from the track.

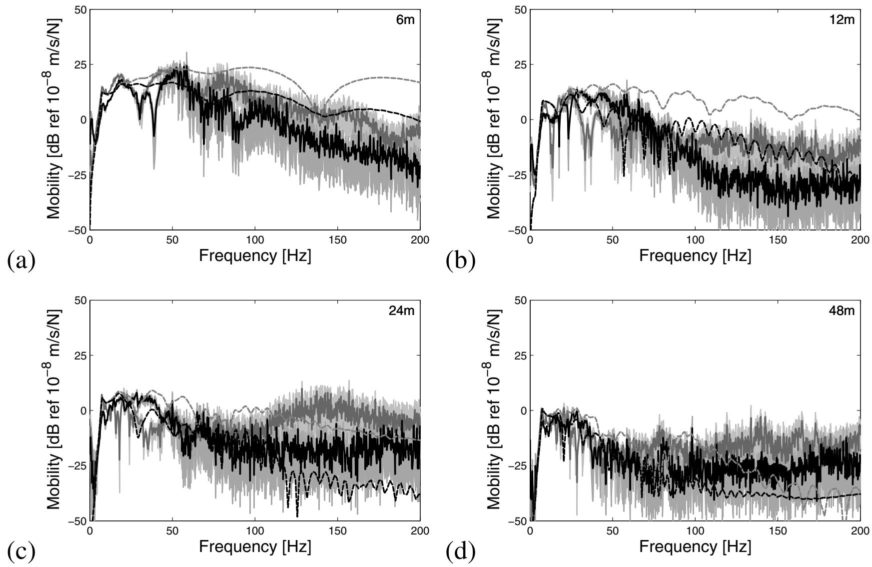


Fig. 1. Transfer functions at (a) 6 m, (b) 12 m, (c) 24 m and (d) 48 m predicted with initial soil profile (dashed grey line) and updated material damping parameters (dashed black line) compared to experimental results for the test section (light grey line) and the reference section (dark grey line). The grey regions indicates the 95 % confidence intervals.

Up to around 50 Hz the confidence interval is relatively narrow which indicates that the measured response clearly exceeds the noise level. Above 50 Hz the confidence interval is wider even at a small distance from the source. The response is attenuated with increasing distance from the source due to geometrical damping, caused by spreading of the vibration energy over a larger area, and material damping, caused by the dissipation of energy in the soil.

2.3 Prediction of Transfer Functions

The free field transfer function is predicted numerically by means of a boundary element model for a layered halfspace coupled to a rigid foundation model [2], shown in Fig. 2(a), based on the identified soil profile. The predicted transfer function is compared to the experimental results (displayed in Fig. 1). A good approximation to the experimental result is obtained for low frequencies. At frequencies above 25 Hz, the measured transfer function is generally overestimated. The discrepancy between the measured and predicted transfer function grows larger for increasing distance from the source, indicating an underestimation of the material damping ratio.

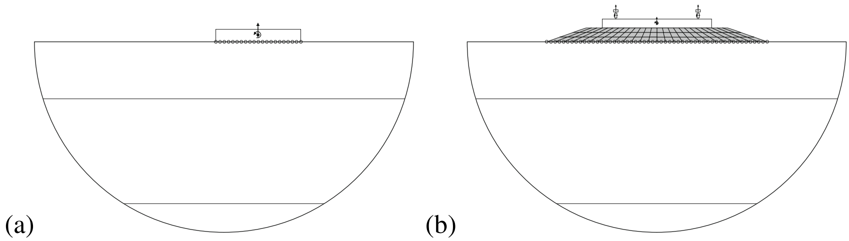


Fig. 2. Schematic view of the prediction model for the free field transfer functions

2.4 Updating of the Material Damping Ratio

In order to obtain a better agreement between measured and predicted transfer functions, the soil's material damping ratio is updated based on the Arias intensity [3] which is a measure for the vibration energy contained in the signal. The updating of the soil's material damping ratio is performed through an inverse procedure in which the predicted Arias intensity is fitted to the experimental Arias intensity.

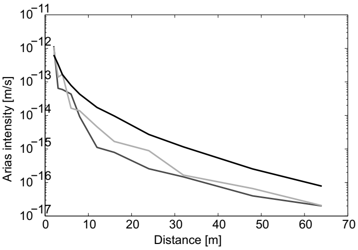
Fig. 3(a) shows the agreement between the predicted Arias intensity based on the initial value of the soil's material damping ratio and the measured Arias intensity at both sections, revealing an underestimation of the material damping ratio.

The difference between the predicted and measured Arias intensity is minimized based on the transfer functions computed at a 1 Hz frequency step in the range between 5 Hz and 50 Hz, applying a lower bound of 0.010 and an upper bound of 0.150 for the material damping ratio. Fitting the Arias intensity at the test section yields the following results for the material damping ratio in each layer:

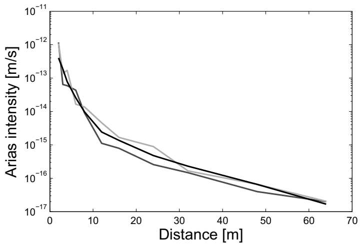
$$\beta_s = \beta_p = \{0.123 \;\; 0.112 \;\; 0.014 \;\; 0.010 \;\; 0.010\}^T$$

The results follow the general expectation that material damping decreases with depth. The imposed lower bound value is reached for the fourth layer and the halfspace. As the wave propagation is mainly concentrated in the top three layers in the frequency range of interest, the significance of the material damping ratio in the bottom two layers is found to be relatively small.

Fig. 3(b) shows that the agreement between the measured and predicted Arias intensity after optimization is very good for both sections, even if the optimization process only takes into account the results of the test section. Including the results of the reference section leads to unrealistic values of the material damping ratio in the first and fourth layer and the supporting halfspace, but hardly affects the resulting prediction of the transfer functions, indicating again the smaller importance of the material damping ratio in these layers.



(a)



(b)

Fig. 3. Predicted Arias intensity (black line) (a) before and (b) after optimization of the soil's material damping ratio, compared to the measured Arias intensity at the test section (light grey line) and the reference section (dark grey line)

2.5 Validation of Transfer Functions

The transfer functions are predicted again using the updated soil's material damping ratio. Fig. 1 compares the prediction results for the initial and updated parameters with the experimental result. A significantly better agreement with the experimental results is observed, especially at a larger distance from the source. The transfer function is predicted accurately up to 50 Hz, above which the response is dominated by noise. The differences between the measured and predicted transfer functions are often smaller than the differences between the results measured at both sections.

3 The Track Receptance

3.1 Description of the Track

The conventional line at the site in El Realengo has a single ballasted track with a wide rail gauge (1.668 m). The rails are of the type RN 45 (stiffness $E_rI_r = 3.00\times10^6$ Nm^2, mass per unit length ρ_rA_r = 44.8 kg/m) and are supported by bi-block reinforced concrete sleepers (mass m_{sl} = 200 kg, rotational inertia $\rho_{sl}I_{sl}$ = 102.4 kgm^2). Rail pads are located between the sleepers and the rails and are initially assumed to have a stiffness $k_{rp} = 300\times10^6$ N/m and viscous damping $c_{rp} = 3.5\times10^3$ Ns/m. The ballast layer of 0.50 m (shear wave velocity C_s = 250 m/s, density ρ_b = 1600 kg/m^3, Poisson's ratio υ = 0.2) is supported by an embankment of 0.50 m (shear wave velocity C_s = 200 m/s, density ρ_e = 1700 kg/m^3, Poisson's ratio υ = 0.35). The stiffness of the rail pad and the shear wave velocity of the ballast are initial estimates and are updated in Section 3.3.

3.2 Experimental Results

The track receptance has been measured in unloaded conditions where a hammer impact is applied on the rail and the corresponding rail response is measured. The dynamic track behavior is strongly affected, however, by the magnitude of the track load. The receptance has therefore additionally been measured when the track is loaded by a train, by measuring the track deflection and the axle loads during the passage of a train. This results in an estimation of 2×10^{-8} m/N for the static track receptance (also shown in Fig. 4).

3.3 Updating of the Track Receptance

The track receptance is predicted by means of a 2.5D coupled finite element – boundary element model [4], shown in Fig. 2(b), where the track and soil are modeled as invariant in the longitudinal direction in order to reduce the computational cost.

Fig. 4 compares the receptance predicted based on the design values presented in Section 3.1 with the measured receptance in loaded conditions. It is clear that the initial track parameters lead to an underestimation of the track receptance, or an overestimation of the track stiffness.

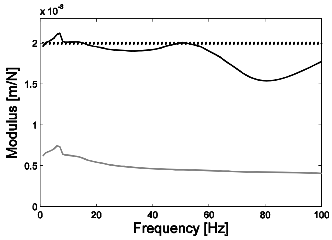


Fig. 4. Predicted track receptance before optimization (grey line) and after optimization (black line) of the track parameters, compared to the track receptance measured in loaded condition during train passages (dotted line)

The parameters of the resilient track components are updated by fitting the predicted and measured results in a frequency range between 0 and 60 Hz, resulting in a ballast shear wave velocity C_s = 150 m/s and a rail pad stiffness $k_{rp} = 31\times10^6$ N/m.

In order to fit the measured track receptance, a decrease in track stiffness is required. This is only achieved by a decrease in the stiffness of the ballast and the rail pad, as they are the only resilient track components considered in the updating process, which results in an unrealistically low value of the rail pad stiffness. Rather than physical characteristics of the ballast and the rail pad, the updated parameters should therefore be seen as input parameters for the present numerical model in order to obtain an accurate prediction.

Fig. 4 shows that the updated track receptance agrees well with the measured receptance between 0 and 60 Hz.

4 Track – Free Field Transfer Functions

4.1 Experimental Results

The track – free field transfer functions are measured at both the reference section and the test section by means of hammer impacts applied at five locations on the rail.

The corresponding ground velocity is measured using geophones installed on five measurement lines perpendicular to the track centerline and corresponding to the five impact locations. Comparison of the transfer function at each measurement line shows that the longitudinal variation along the track is limited. Fig. 5 shows the measured transfer functions and the 95 % confidence interval for the reference section and the test section at 10 m, 16 m, 24 m and 48 m from the track at the central measurement line. At 10 m a narrow confidence interval is found up to 125 Hz, indicating that the measured response clearly exceeds the noise level, while at 48 m a narrow confidence interval is found only up to 50 Hz.

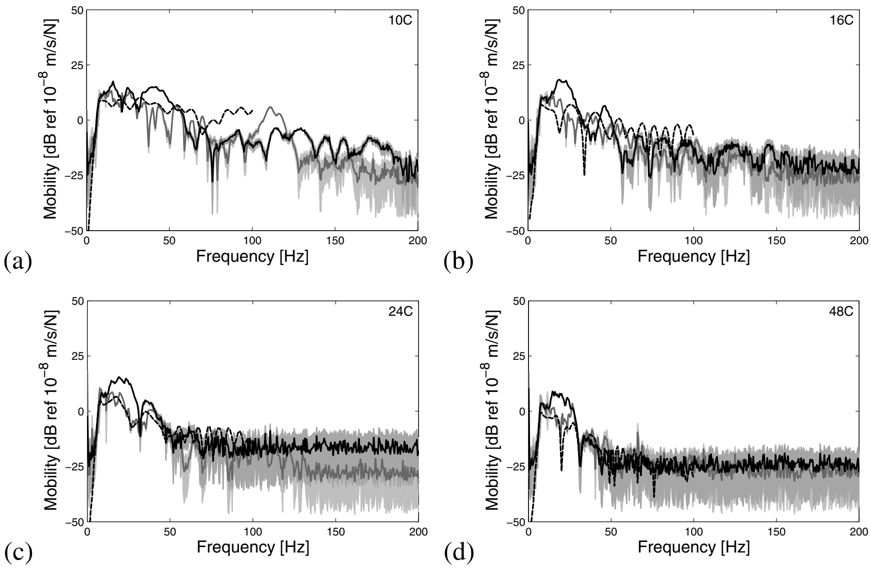


Fig. 5. Transfer functions at (a) 10m, (b) 16 m, (c) 24 m and (d) 48 m from the track predicted with updated track parameters (dashed line) compared to experimental results for the test section (light grey line) and the reference section (dark grey line). The grey regions indicates the 95 % confidence intervals.

4.2 Validation of the Transfer Functions

The free field transfer function is predicted numerically by means of the 2.5D coupled finite element – boundary element model [4] (Fig. 2b). The transfer functions are predicted based on the updated track parameters, presented in section 3.3. Fig. 5 compares the predicted transfer functions with the experimental result. The misfit between the prediction and the experimental results is often smaller than the difference observed between the transfer functions at both sections. Generally, good prediction accuracy is obtained based on the identified soil and track characteristics.

5 Conclusions

Benchmark tests carried out at a site in El Realengo (Spain) show that an accurate prediction of the vibration transfer is obtained based on identified soil and track characteristics. Updating of the soil's material damping ratio improves the prediction accuracy. Updating of the track parameters strongly affects the track receptance but only has a small effect on the track – free field transfer functions.

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