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Train Mitigation Measures in the Transmission Path: Seismic Metamaterial and Granular Barriers

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ABSTRACT

The development of new mitigation measures is an effective solution to the annoyance generated by the induced vibration coming from the railway traffic to the residents of urban areas. This paper aims to give a brief comparison of two novel concepts of mitigation measures applied within the transmission path presented recently in the literature. In particular, the use of seismic metamaterial will be compared to the use of heterogeneous barriers, to evaluate to which extent these two mitigation measures can help to tackle the problem of ground-borne vibration and noise. These two cases will be related by considering the same railway environment based on a two-step approach, already validated in the past; in this study, the soil simulated in the second step is reproduced using the finite element method and spectral element method for the seismic metamaterial and heterogeneous barriers respectively. Finally, a parametric investigation is conducted to understand how the material and geometrical proprieties affect the attenuation levels of the two measures.

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1. INTRODUCTION

The railway industry has been characterized by an exponential increase in the past years due to its sustainability, and this positive trend is expected to continue in the future for which Europe aims to cover 50 % of the total land transportation by rail lines by 2050 [1]. In order to permit the realization of this ambitious goal, engineers have to deal with the environmental issues caused by this ecological mode of transportation. In particular, railway traffic is responsible for vibration emissions in the vicinity of railroad tracks, which represents one of the main drawbacks of this mode of transportation [2, 3].

The interaction of trains, tracks, and subsoil causes ground-borne vibration, (which is the type of "vibration" that is most frequently felt). The vibration then travels through the ground and gets to the nearby building's foundations. The building responds to the foundational vibration, which is then transmitted through the structure of the building and can be seen in the oscillation of the floors and walls, as depicted in Figure 1.

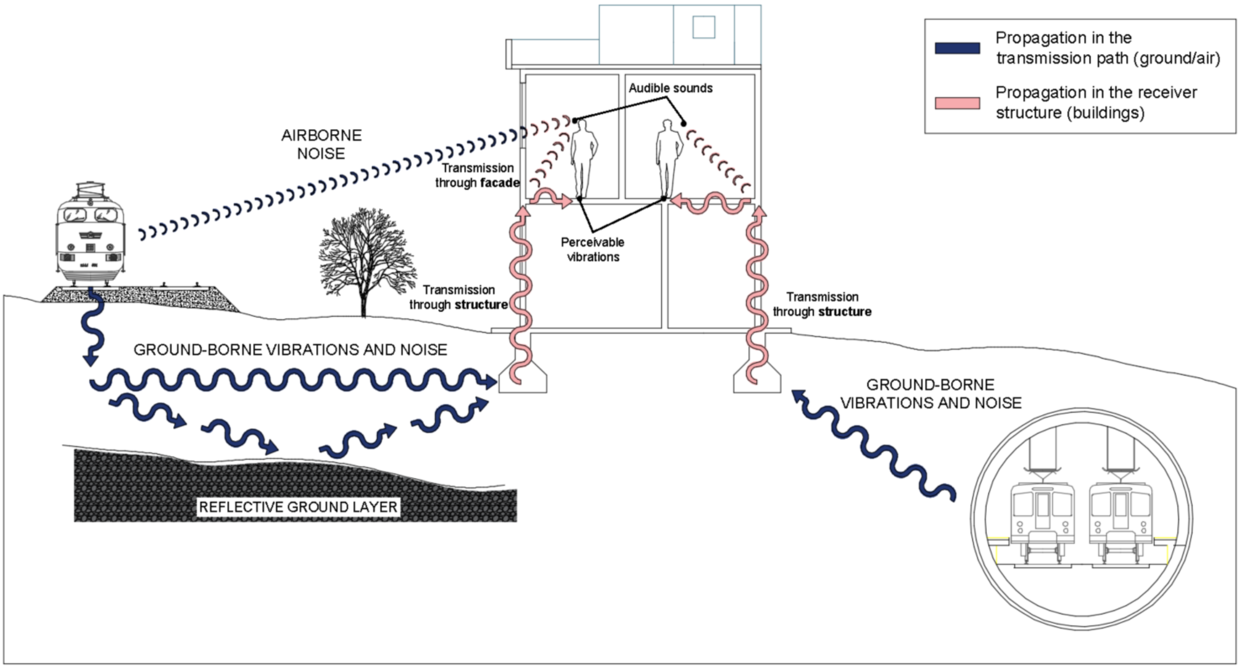


Figure 1: Surface and underground railway mechanism effects and transmission paths of air-borne noise and ground-borne vibrations and noise [2].

Different researchers have investigated ways to mitigate the vibrations generated by the railway industry, with measures applicable to all the subdomains of the railway environment such as vehicle [4], track [5], transmission path [6], and receiver [7]. Ouakka et al. [2] have extensively summarized the different mitigation measures that can be used to attenuate these effects. Mitigation measures on the propagation path such as trenches or barriers are particularly interesting because they do not modify existing structures (tracks or buildings). Trenches isolate better than barriers [8] but present long-term stability problems such as the risk of collapse or filling with rainwater. The use of classical filling materials allows us to solve these stability problems, however, the required depth, evaluated in terms of Rayleigh wavelength, leads in homogeneous soil to unrealistic depths [9].

This paper focuses on the comparison between two new types of barriers recently proposed for railway-induced vibration. The first one is based on the use of periodic barriers [10, 11] and the second one is based on the use of a heterogeneous barrier [12]. In particular, based on the already validated two-step approach the railway environment is reproduced. Firstly, a mono-wheel vehicle running on a ballasted track is considered and then the vibration wave propagation is investigated in the second step by using different methods. The spectral element method and the finite element method where the heterogeneous barrier and the periodic barriers are respectively introduced. Finally, the attenuation level of the two mitigation measures is evaluated and compared in the case of the same encumbrance for the two cases.

2. NUMERICAL APPROACHES

Different approaches are available in the literature to reproduce the railway environment and to predict ground-borne vibrations. Among these the most suitable where shown to be the numerical model able to separate the three main subdomains (vehicle, track, and transmission path) of the railway environment, as depicted in Figure 2.

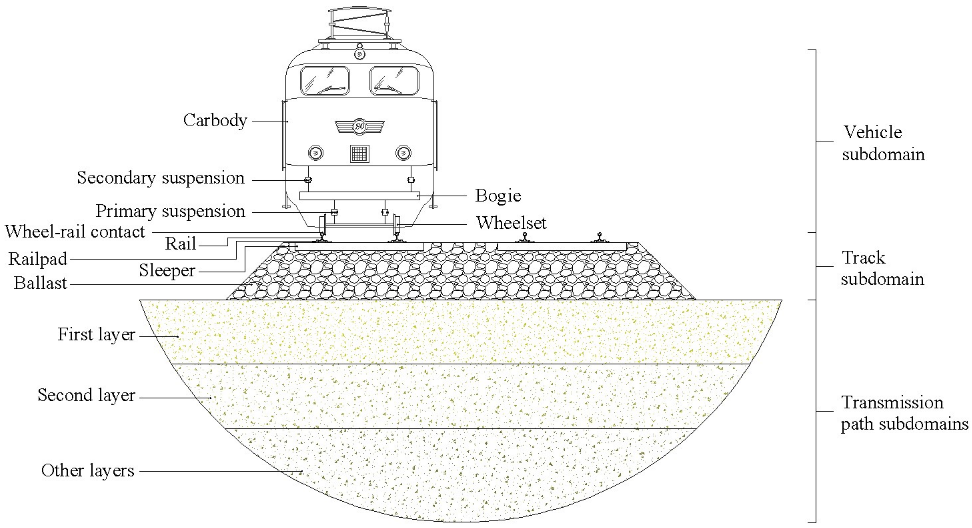


Figure 2: Longitudinal section view of the vehicle/track/soil subdomains.

In particular, the two-step approach will be adopted. This approach consists of two different steps, as depicted in Figure 3. Firstly the vehicle/track subsystems are modeled with the in-house framework to compute the forces applied by the track to the soil. Whereas, in the second step the outputs of the first step, which represent the forces acting on the soil, are applied to the soil. In this study, the soil is modeled using two different element methods in order to compare the two mitigation measures developed in past research using the respective methods. The implementation of periodic barriers into the soil has been investigated by Ouakka et al. [11] using the commercial finite element software ABAQUS, whereas the granular barriers have been studied using the spectral element method as presented by Dec et al. [13]. First, these two approaches have been validated on the same reference case without a barrier. Then, barriers have been introduced in both models.

2.1. First Step

In the first step, the vehicle/track subdomains are developed with the Multibody approach using the in-house C++ framework EasyDyn for both cases. In particular, the simple case of a mono-wheel with a total mass of 1500 [kg] and moving at 150 km/h is considered in this study, as depicted in Figure 4 [15].

Whereas the track proprieties are considered as the work presented by Ouakka et al. [10], summarized in Table 1. Defined as a flexible rail (Youngs modulus E_r, a geometrical moment of inertia I_r, a section A_r and a density ρ_r), laying in the lumped mass m that plays the dynamic role of sleepers. The link between the rail-sleeper (rail pad) and sleeper-soil (ballast) is represented by a spring-damper system, respectively defined by its stiffness (k_p,k_b) and its damping (d_p,d_b). The wheel-rail forces are defined using non-linear Hertzs theory including the geometry of the potential defects, that allows the vertical coupling between the vehicle model and the track.

The obtained load is then used in the second step by both models. Figure 5 presents an example

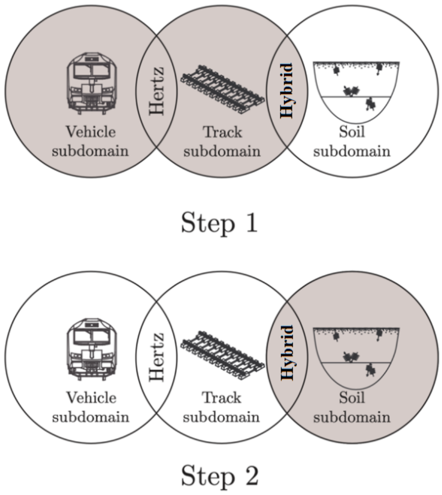


Figure 3: Vehicle/track/soil model, decoupled between the ballast and the soil [14].

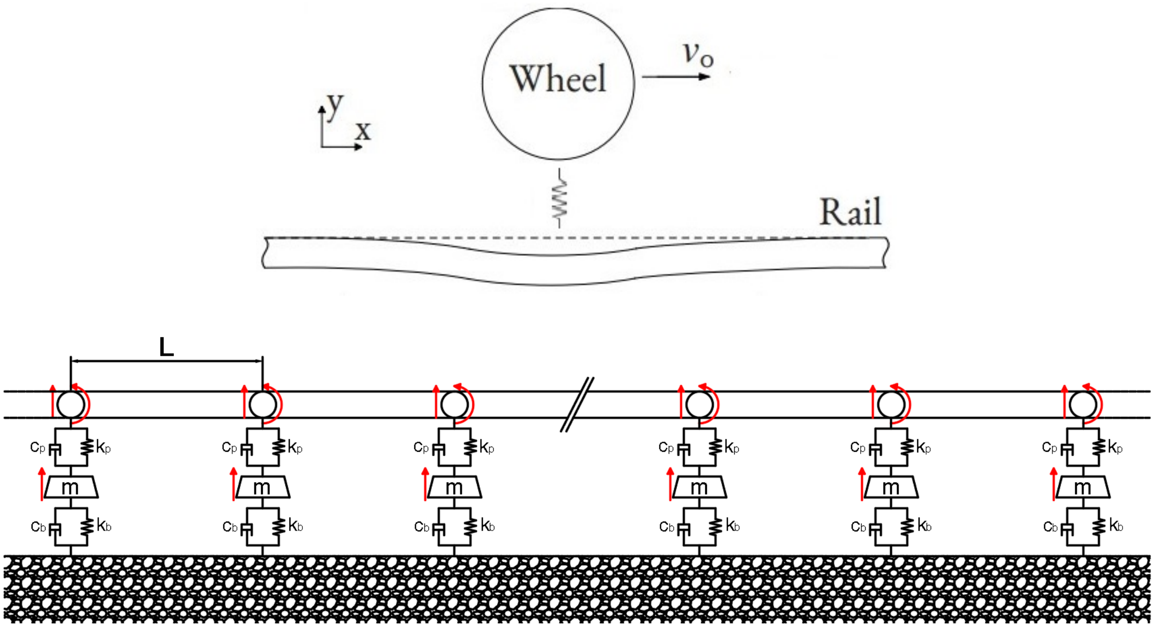


Figure 4: Mono-wheel vehicle at a speed v_0 and track/foundation coupling

Table 1: Dynamic properties of the ballast track.

E_r	I_r	A_r	ρ_r	L
210 [GN/m^2]	1988 [cm^4]	0.00638 [m^2]	7850 [kg/m^2]	0.72 [m]
c_p	k_p	m	c_b	k_b
30 [kNs/m]	90 [MN/m]	90.84 [kg]	40 [kNs/m]	25.5 [MN/m]

of the applied load the time history and its respective frequency content. Notice that a filter in the range of 4 to 100 [Hz] is used to avoid extreme frequencies which are not relevant for the investigation of the ground-borne vibration.

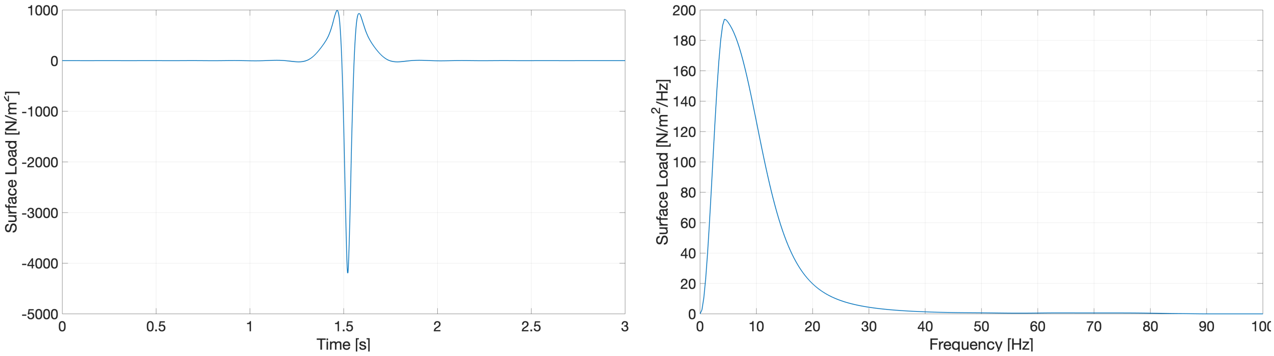


Figure 5: Time history (left) and spectrum (right), of an example of load applied at one sleeper position.

2.2. Second Step

The second step is taken with two different approaches in order to achieve the aim of this paper of comparing two different mitigation measures which have been investigated in the literature with two different approaches.

– **Finite Element Method**

The soil is modeled using FEM when the periodic barriers are considered. Here the soil is modeled as a half-space with an outside region made up of infinite elements that serve to replicate the behavior of an infinite domain and an inner region made up of conventional finite components. The finite-element program ABAQUS is used to simulate the induced vibrations from the rail foundation in the current investigation. In order to connect the internal (finite) domain to the external (infinite) one, this software employs the necessary mapping formulation [16], eliminating pertinent reflection and correcting for any potential mapping errors [17].

– **Spectral Element Method**

Wave propagation problems when heterogeneous barriers are considered to have been solved using SEM3D software [18] based on the Spectral Element Method [19] and co-developed by MSSMat Laboratory (CentraleSupélec, CNRS, and Université Paris-Saclay), Institut de Physique du Globe de Paris (Paris Institute of Earth Physics) and the Commissariat à l'Énergie Atomique et aux énergies alternatives (French Atomic Energy Commission). The SEM is a FEM that uses Lagrange polynomials of high order over each element of the mesh. The nodes of the Lagrange polynomials are those of the Gauss-Lobatto-Legendre quadrature. The integrals are evaluated using the same quadrature which leads to a diagonal mass matrix. This method is restricted to conformal meshes composed of hexahedral elements in 3D. Perfectly Matched Layers are used to simulate wave propagation in an unbounded domain.

3. MODEL DATA SETTING AND VALIDATION

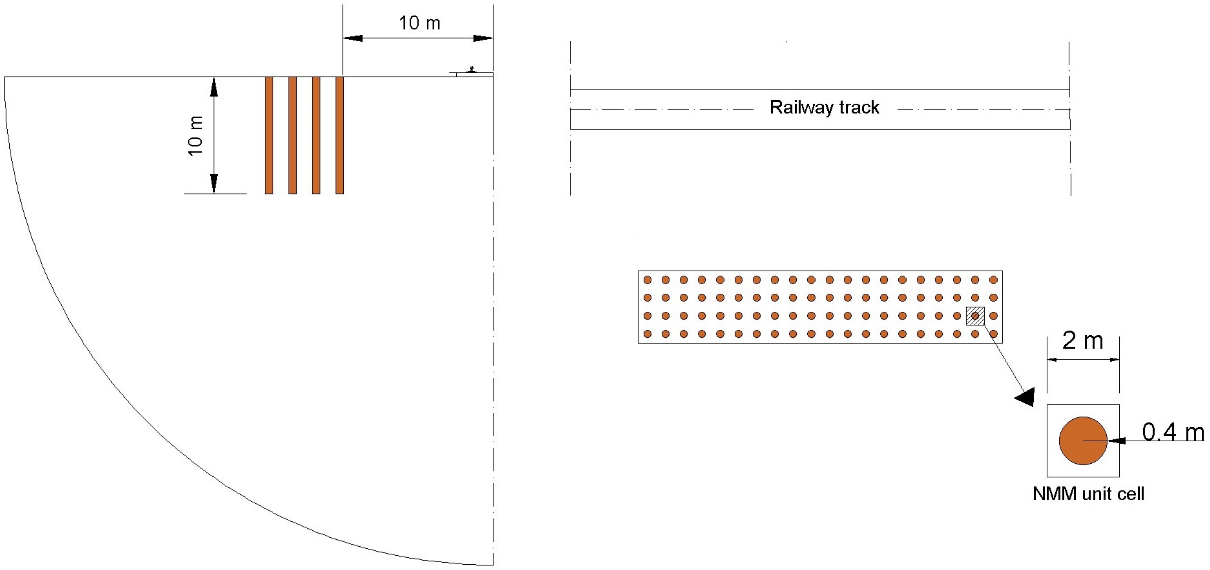
Before moving to the analysis of the attenuation levels of the two different mitigation measures, in this section, the agreed data sets are presented in order to reproduce the same railway scenario with both element methods.

3.1. MODEL DATA SETTING

In both models, the soil is assumed linear, elastic, and homogeneous with pressure wave velocity C_P = 397 [m/s], shear wave velocity C_S = 190.7 [m/s], and density ρ = 1700 [kg/m^3]. Barriers 10 [m] deep and located 10 [m] from the track were considered.

– **Periodic barrier**

Figure 6 presents the 3D Finite Element model of the soil and introduction of the concrete periodic barriers. In particular, the soil is represented by a quarter of q sphere with a radius of 50 [m], with the included periodic barrier composed of a number of nine columns and four rows, which corresponds to a total encumbrance of 7 [m] in width and 20 [m].



(a) Section view

(b) Bird eye view

Figure 6: Distribution of the trees array in the model, with details of the natural metamaterial units.

The characteristics of the concrete inclusion are as follows: Young's Modulus = 40 [GPa], Poisson ratio = 0.2, and Density = 2500 [Kg/m^3].

– **Heterogeneous barrier**

Figure 7 presents the 3D model of the soil with the heterogeneous barrier. The width of the barrier is 7 [m] and the length is 20 [m]. The mitigation efficiency of the barrier will be evaluated using one sensor behind the barrier: $S20$ located 20 [m] from the center of the track respectively. The material filling the barrier is assumed to be a randomly-fluctuating continuous elastic medium [20]. The average properties of the random fields of the barrier are C_P = 4215 [m/s], C_S = 2582 [m/s] ρ = 2500 [kg/m^3]. The first-order marginal density of the random fields considered is a log-normal. The coefficient of variation is $CV = 1.5$ and the correlation length is $l_c = 0.8$ [m]. Figure 8 presents the random realization of the compressive wave velocity.

The soil is represented by a box of dimensions 40 m × 100 m × 16 m with a mesh size of 1 [m]. This box is surrounded on five sides by PMLs with a thickness of 90 [m]. The mesh size in the barrier is 0.8 [m]. Lagrange polynomials of 4th-order in each space dimension are used which gives 375 degrees of freedom per hexahedral element in 3D. The total number of hexahedral elements is about $7.2{\times}10^6$. The time step of the simulation is $3.65{\times}10^{-6}$ [s].

3.2. VALIDATION

In this part, the two models are validated for a load moving on a half space without a barrier.

Figure 9 compares the time history and the corresponding Fourier Transforms of the vertical displacement induced in the soil at the sensor $S20$ for both models. A good agreement is obtained between the SEM and FEM models

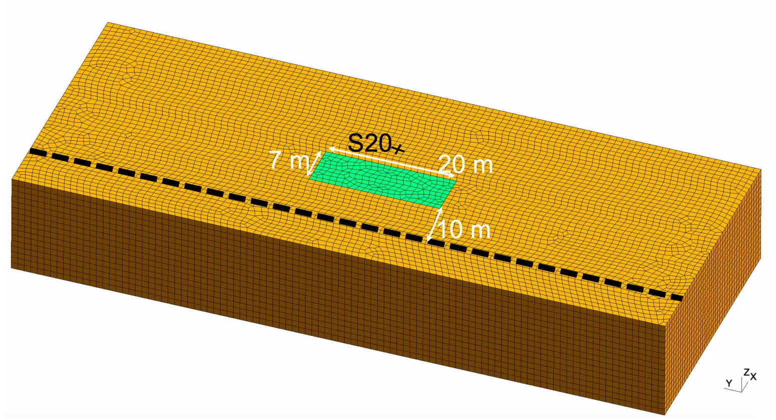


Figure 7: 3D model of the soil. PML are not represented. The dashed line represents the center of the track. Sensors are represented by the black crosses ($S5$: 5 m from the center of the track, $S24$: 24 m from the center of the track and $S32$: 32 m from the center of the track)

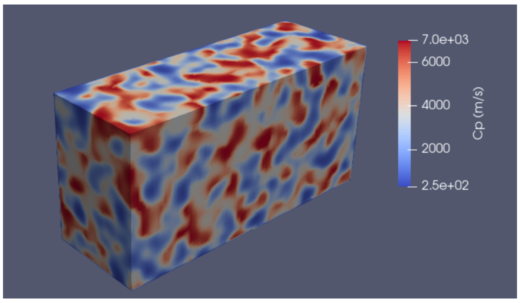


Figure 8: Random realization of the pressure wave velocity C_P of the barrier

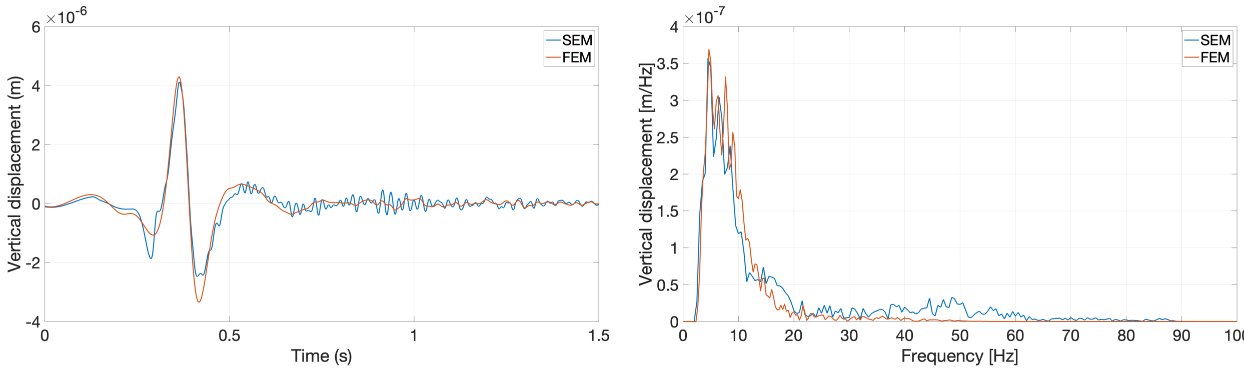


Figure 9: (Left) Time domain and (Right) corresponding Fourier Transforms of displacement induced at 20 m from the track for both models without barrier.

4. RESULTS

In this section, the vibration attenuation efficiency of a periodic barrier is compared to that of a heterogeneous barrier, in terms of insertion losses defined as:

$$\mathrm{IL}(\mathbf{x}, \omega) = 20 \log_{10} = \left| \frac{\hat{u}_Z^{\mathrm{ref}}(\mathbf{x}, \omega)}{\hat{u}_Z^{\mathrm{Trench}}(\mathbf{x}, \omega)} \right| \tag{1}$$

where $\hat{u}_Z^{\mathrm{ref}}(\mathbf{x}, \omega)$ is the Fourier transform of the vertical displacement of the ground surface without the barrier and $\hat{u}_Z^{\mathrm{Trench}}(\mathbf{x}, \omega)$ is the Fourier transform of the vertical displacement of the ground surface with the barrier.

Figure 10 shows some divergence between the two methodologies. In particular, the heterogenous barrier presents a good level of attenuation starting from low frequencies. Whereas, the

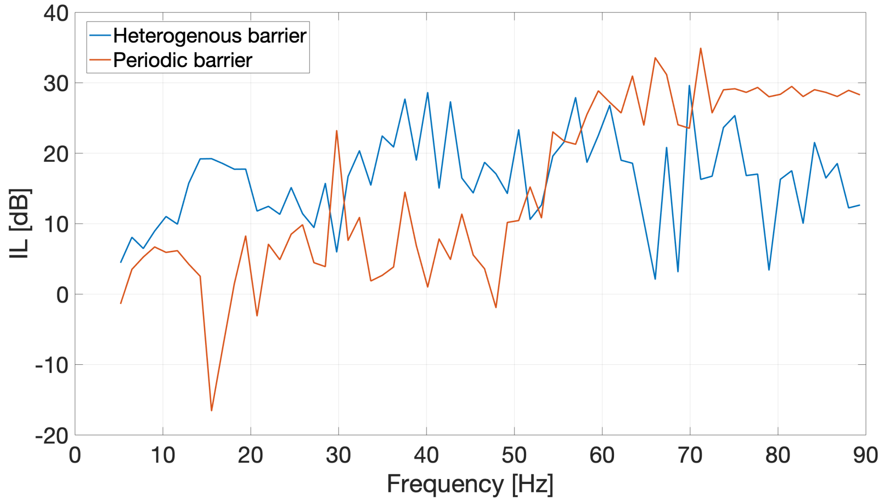


Figure 10: Comparison of insertion losses for the heterogeneous and the periodic barrier

periodic barrier with the chosen configuration exhibits a higher level of attenuation above 50 [Hz]

5. CONCLUSIONS

In this paper, two alternative solutions to homogeneous barriers have been presented to mitigate railway-induced vibrations in the propagation path. The first one is to use periodic barriers and the second one is to use heterogeneous barriers. These two solutions were implemented and studied using the FEM and SEM respectively. First, a reference case of wave propagation waves in a homogeneous half-space was used to validate both models. Then the influence of both types of barriers on the vibration field was studied.

From the results of the case of the monowheel model considered in this study, both mitigation measures showed good levels of attenuation in terms of IL. this research presents the first insights into the comparison of these two methodologies, yet, additional parametric investigations are required in order to have a comprehensive correlation of the two in order to offer criteria to engineers of which of the two is more suitable depending on the project characteristics.

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