NUMERICAL DEVELOPMENT AND EXPERIMENTAL CHARACTERISATION OF A LOW HEIGHT BARRIER FOR RAILWAY NOISE MITIGATION

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ABSTRACT

The increasing use of railways for transporting people and goods is essential to achieve more environmentally and economically sustainable mobility. However, issues related to noise pollution caused by train traffic need to be mitigated to maintain a healthy coexistence between inhabitants and trains.
This paper presents the characterization of a low-height acoustic barrier to be used in a railway environment, numerically developed in a first phase using 2D BEM and which bases its working principle on the curved geometry, capable of sending a large amount of energy back to the track. The solution is placed close to the noise source and takes advantage of the ballast to increase the efficiency of the developed solution. The numerical results show Insertion loss levels in the order of 10 dB for a set of receivers close to the track. The experimental campaign with the prototypes developed on a section of the Sintra line, in Portugal, corroborates the results obtained numerically.
For the various records obtained from the passage of numerous trains, Insertion loss values higher than 10 dB were obtained for the frequency range between 400Hz and 4000 Hz.

Key words— Low-height railway noise barriers, Railway noise, Mitigation measures

1. INTRODUCCIÓN

The railway system is known for being an eco-friendly mode of transportation that utilizes minimal energy. However, a major issue that continues to plague the system is the high noise levels it generates [1, 2]. While acoustic barriers have been implemented to combat this problem, their height can pose a challenge, nevertheless the use of low height acoustic barriers is a solution with proven efficiency for this problem [3, 4]. Therefore, the development and optimization of low-height acoustic barriers using the Boundary Element Method (BEM) and experimental testing is the focus of this work.
Previous studies have shown that low-height barriers can be a viable alternative to traditional acoustic barriers [3-7]. By utilizing a numerical model, we can better understand how sound waves [6, 8, 9] interact with the barrier and determine the most effective solution for reducing railway noise.
The barrier's design takes advantage of the railway system's elements, leveraging the acoustic properties of the ballast to absorb sound waves and redirect energy towards the track. Prototypes were constructed and tested in both free-field and railway environments. While free-field tests showed high levels of insertion loss, testing the barrier in isolation resulted in efficiency losses at certain frequencies.
However, in railway environment tests, the barrier's effectiveness was evident, with insertion loss values of at least 10 dB across a frequency range of 400 Hz to 4000 Hz. This clearly demonstrates that the barrier can be an effective tool in reducing railway noise when integrated into the railway system.

2. NUMERICAL DEVELOPMENT OF THE BARRIER

The development of the barrier was carried out using the Boundary Element Method (BEM). This method offers significant potential for solving acoustic problems, enabling analysis of complex geometries [9, 10]. The method just requires only the discretization of boundaries and discontinuities within the medium. The determination of acoustic variable values at the boundary and within the medium is accomplished using Green's functions.
The barrier's geometry was designed for optimal efficiency, leveraging the physical properties of sound waves. Thus, the

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focus is on favoring the normal reflection of waves on the barrier's surface, redirecting as much energy as possible back to the track. To achieve this, a numerical simulation of a sound wave affected by the presence of the vehicle and the railway track was conducted as illustrated in Figure 1. The inner face of the barrier was then designed to coincide with the wavefront geometry and achieve the desired objectives. More detailed information about this process can be found in [11, 12]**.** In addition the barrier height was set at 1.20 m to ensure a harmonious coexistence between the mitigation solution and the resident population. Lastly, the distance between the barrier and the track, which greatly impacts the solution's performance, was established in accordance with safety considerations, and it was set at approximately 1.23 m between the rail and the barrier.

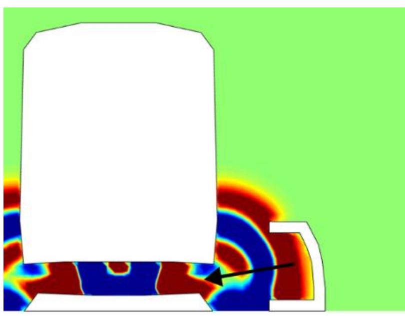

Figure 1 - Sound wave simulation diagram for defining the barrier geometry.

Additionally, for the definition of the numerical model, the following considerations were taken: for the ballast, an absorption coefficient was considered according to experimental data from reference [13]. It is assumed that both the vehicle and noise barrier have zero absorption coefficients due to their complete reflectivity in practice. In order to evaluate the acoustic performance of the barrier, the Insertion Loss was calculated for an array of receivers located approximately 7 meters away from the track. The array spans around 6 meters horizontally and 3 meters vertically, as illustrated in Figure 2.

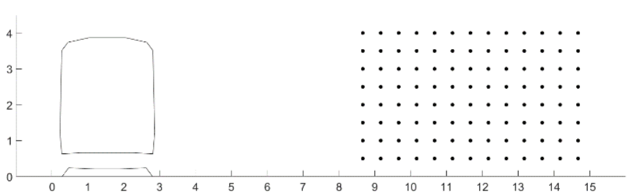

Figure 2 - Representation of the mesh of receivers used to calculate Insertion loss.

The average Insertion loss was calculated for the receiver array described earlier, covering frequencies from 400 Hz to 4000 Hz. The outcomes are illustrated in Figure 3. It can be seen that values greater than 10 dB were achieved across the frequency range under investigation. For lower frequencies, the values remain between 10 dB and 15 dB, with a slight dip at 1000 Hz. As the frequencies increase, there is a gradual rise in the insertion loss, reaching a peak of around 18 for the frequency 3000 Hz.

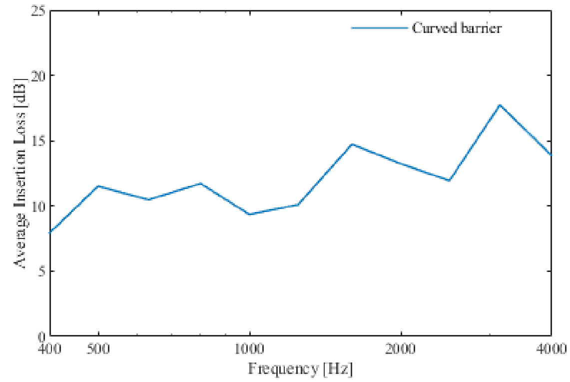

Figure 3 - Average insertion loss calculated for the low height curved barrier.

3. EXPERIMENTAL RESULTS IN FREE FIELD

3.1. Measurement setup

The field-free experimental campaign allows for testing the barrier in a controlled environment, aiming to achieve insertion loss levels as realistic as possible. It should be emphasized that this experimental study solely focuses on the presence of the barrier as a stand-alone element.

The receivers were located at six distinct points. In the first configuration, three receivers were situated at a height of 1.5 meters, positioned at distances of 1.5 meters, 4.5 meters, and 7.5 meters from the acoustic barrier, respectively. The second configuration maintained the same distances from the barrier but positioned the microphones at a height of 2.35 meters, as illustrated in Figure 4. Lastly, in terms of the alignment of the barrier, five barrier modules were positioned and aligned, spanning a total length of 12 meters. A layer of sand was prepared to facilitate the placement of precisely leveled and aligned barriers. Silicone was used between the modules to prevent the passage of waves through the dry joints.

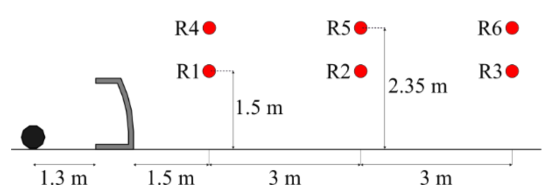

Figure 4 - Representation of the measurement setup used in the free field.

3.2. Results of the experimental campaign on free field

The Insertion Loss values are elevated, surpassing 10 dB for higher frequencies, and demonstrating greater variability for lower frequencies. A dip is noticeable around the 1000 Hz frequency across all receivers. The Figure 5 through Figure 10 depict the outcomes obtained for each receiver. The results for receiver number 1 (R1), showcased in Figure 5, exhibits Insertion Loss levels exceeding 10 dB for most of the frequency range. However, a reduction in the barrier's effectiveness is seen within the 800 Hz to 1200 Hz range, resulting in minimum IL values of 5 dB. The Insertion loss levels of the receiver number 2 (R2) (see Figure 6) displays a behavior similar to R1, with Insertion Loss exceeding 10 dB for most frequencies. Notably, the 400 Hz to 800 Hz and 1500 Hz to 4000 Hz ranges stand out. A dip in efficiency reappears in the 1000 Hz to 1250 Hz frequency span, registering an IL value of 5 dB.

For receiver number 3 (R3) (see Figure 7), located farthest from the barrier, Insertion Loss values surpass 10 dB for lower frequencies (400 Hz to 1000 Hz). A decline in IL levels occurs from 1000 Hz, with a value of 5 dB within the 1600 Hz to 2000 Hz range. Higher frequencies again yield IL values slightly exceeding 10 dB. A significant drop in barrier performance is observed at 1250 Hz, with an almost negligible IL value in this one-third octave band. The position reduces barrier protection and magnifies the influence of direct waves from the source.

Receiver number 4 (R4) (Figure 8), situated 1.5 meters from the barrier, is notably affected by both direct and diffracted waves. As a result, attenuation is relatively low, with IL values close to zero or negative. However, frequencies above 1250 Hz demonstrate IL values nearing 10 dB. Despite a dip and slight amplification at 800 Hz, the barrier exhibits considerable mitigation capabilities, especially since this receiver is in a transitional zone.

For receiver 5 (R5) (Figure 9) and receiver 6 (R6) (Figure 10), positioned farther from the barrier, the mentioned instability is less pronounced. Receiver 5 showcases IL values exceeding 10 dB for the 400 Hz to 800 Hz and 1500 Hz to 4000 Hz ranges. A dip in the 1000 Hz to 1250 Hz range exhibits IL values around 4 dB. For receiver 6, the results point out values above 10 dB for most of the frequency range, with emphasis on low and high frequencies.

In conclusion, the analysis demonstrates that the majority of receivers exhibit notably high IL values. It is important to emphasize once again that these results relate to the assessment of the barrier as an isolated element. Since the solution was designed to take advantage of the properties of the surrounding system, the results obtained are affected by the non-presence of both the track and the vehicle.

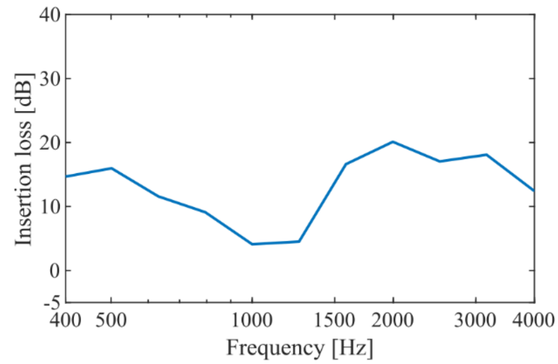

Figure 5 - Insertion loss for receiver R1.

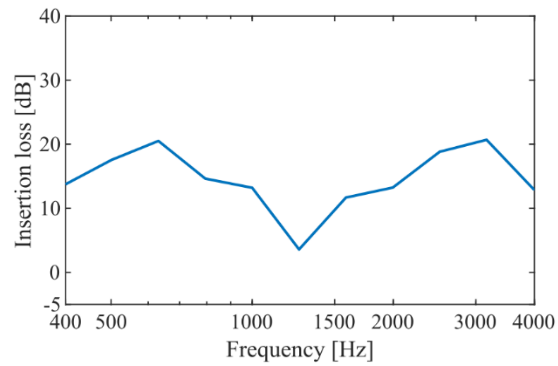

Figure 6 - Insertion loss for receiver R2.

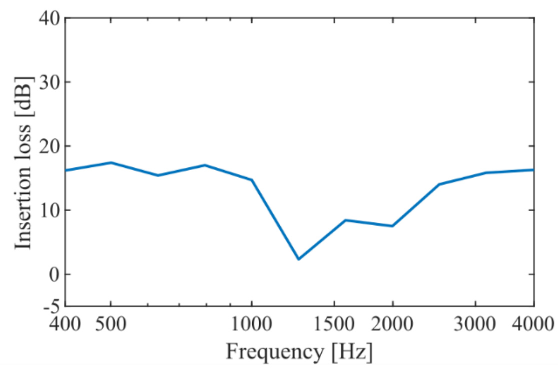

Figure 7 - Insertion loss for receiver R3.

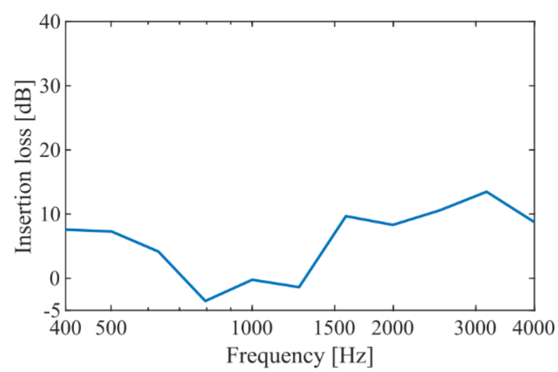

Figure 8 - Insertion loss for receiver R4.

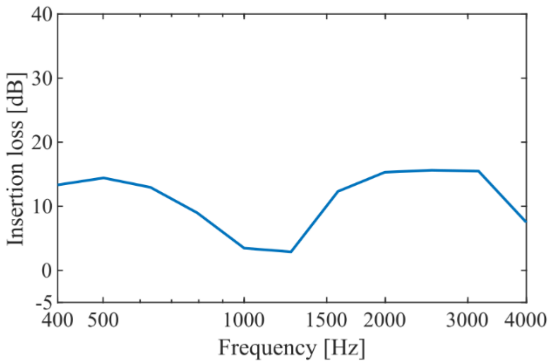

Figure 9 - Insertion loss for receiver R5.

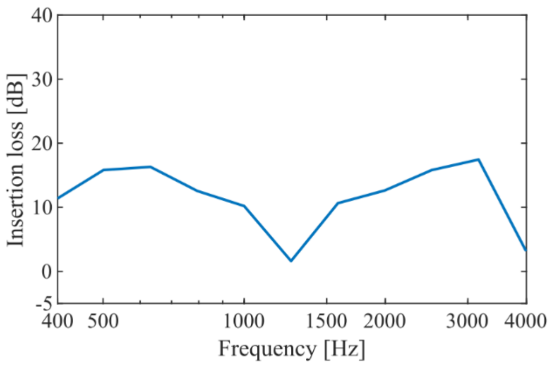

Figure 10 - Insertion loss for receiver R6.

4. EXPERIMENTAL RESULTS IN RAILWAY ENVIRORMENTAL

The experimental campaign conducted on the Sintra railway line in Portugal plays a crucial role in enhancing the comprehension of the barrier's functionality. Prototype acoustic barriers were installed along a section of the Sintra railway line at kilometer point PK23+760. This railway line connects the cities of Sintra and Lisboa and experiences substantial urban traffic.

In terms of infrastructure, the track consists of a double ballast surface designed to accommodate urban passenger transport vehicles. The speed range at this location varies between 60 km/h and 90 km/h. The Figure 11 provides a photography of vehicle circulating on the Sintra railway line in measurement site.

Figure 11 - Photography of the barrier and the train on the Sintra line.

The noise barrier prototype was implemented on an 80 m alignment and was divided into three parts to accommodate safety requirements. This division was primarily done to create a safe distance from a catenary pole. The first and third alignments, comprising 15 barrier modules each, are located 1.60 m away from the outer rail. The second alignment, which is aligned with a catenary pole, is positioned approximately 3.16 m away from the outer rail. Taking into account the positioning of the barrier alignments, a reference microphone was positioned outside the area of influence of the barriers (Microphone 1) and two microphones were positioned behind each of the barrier alignments, in this case microphone 2 and microphone 3 according to Figure 12.

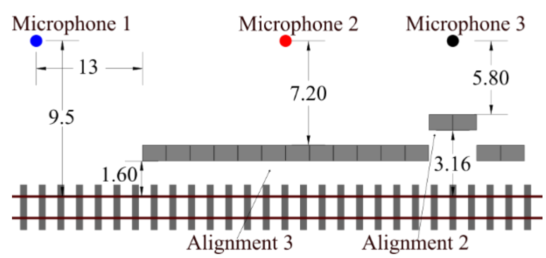

Figure 12 - Representation of the measurement setup used in the railway environment.

4.1. Results of the experimental campaign on Sintra railway line

4.1.1 Analysis of the indicator $L_{Aeq,T}$

The speed of the train plays a decisive role in determining noise levels and the effectiveness of the acoustic barrier. By calculating the equivalent continuous sound level $L_{Aeq,T}$ for each passing train, the barrier's efficiency can be assessed. This involves comparing the indicator value within the barrier's influence area with that of the microphone positioned outside this area. The Figure **13** and the Figure **14** illustrates the $L_{Aeq,T}$ indicator corresponding to train passages through the measurement section regarding all recorded instances. These passages occur in both the Sintra-Lisbon

direction (closer to the barriers) and the Lisbon-Sintra direction (farther from the barriers).
Firstly, upon analyzing Figure **13Erro! A origem da referência não foi encontrada.**, a distinct correlation between the rise in the $L_{Aeq,T}$ indicator value and the train's operating speed becomes evident. This increase manifests both at the microphone positioned outside the barrier's influence area and at the receivers situated in the shadow zone of the prototype. Secondly, a closer examination of the mentioned Figures, reveals a noticeable reduction in the $L_{Aeq,T}$ indicator values. For microphone 1, positioned beyond the barrier's influence area, the indicator value is approximately 90 dBA. Conversely, for each microphone placed behind the barrier, the indicator is approximately 80 dBA for microphone number 2 and slightly lower, approximately 75 dBA, for microphone number 3. This signifies a reduction of at least 10 dBA in the readings captured by the microphones positioned within the barrier's influence area.
For vehicles traveling along the track farther from the acoustic barriers, in the Lisbon-Sintra direction (see Figure 14), the $L_{Aeq,T}$ values are lower for the microphone outside the barrier's influence area due to the increased distance. However, they generally surpass 80/85 dBA. Concerning the microphones situated behind the barrier, a decrease in the indicator ranging from 5 dBA to 10 dBA is observed. The smaller reduction is attributed to the greater distance between the barrier and the track. Nonetheless, given the 1.20 m height of the barriers, the considered travel speeds, the outcomes are notably favorable, showcasing substantial reductions in noise levels. In summary, the indicator indicates reductions ranging from 10 dBA to 15 dBA for vehicles in proximity to the barrier, while for vehicles traveling farther along the track, the reduction lies between 5 dBA and 10 dBA.

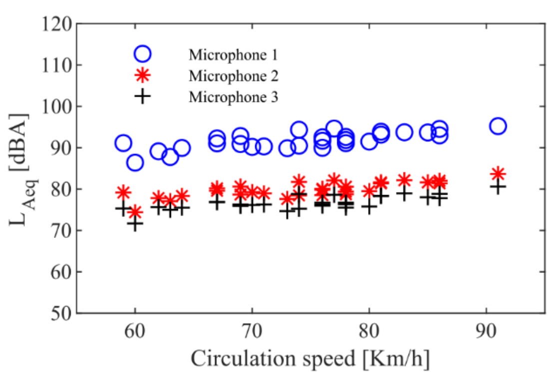

Figure 13 - $\mathbf{L_{Aeq,T}}$ value for vehicles traveling close to the barrier.

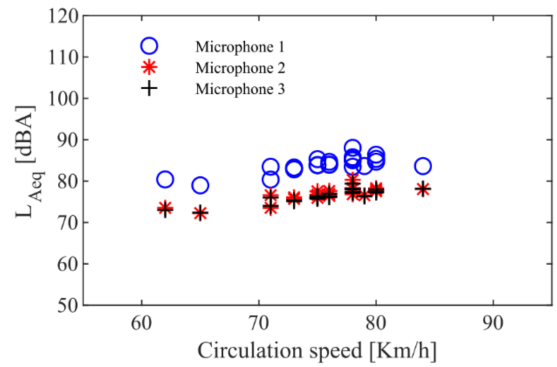

Figure 14 - $\mathbf{L_{Aeq,T}}$ value for vehicles traveling away to the barrier.

4.1.2 Analysis of the Insertion loss

Regarding the Insertion Loss values, firstly for vehicles traveling in Sintra-Lisbon direction (closer to the barriers), for microphone 2 (depicted in Figure 15), IL levels hover around 10 dB across most of the frequency range. A minor decline is observable between 500 Hz and 800 Hz, registering minimum IL values around 8 dB. Notably, this particular receiver exhibits maximum mitigation at higher frequencies, stabilizing at approximately 15 dB.
Analyzing the microphone 3 (shown in Figure 16), the aforementioned receiver follows a similar mitigation trend, albeit with slightly elevated IL values. Despite its more distant placement from the track, the Insertion Loss consistently exceeds 10 dB across all frequencies. It's noteworthy that the rise in IL for microphone 3 compared to microphone 2 can be attributed to their respective distances from the alignment. This disparity can be elucidated by the creation of a shadow zone resulting from the full barrier alignment. Positioned at the precise midpoint of the total barrier alignment, microphone 3 benefits from heightened protection in comparison to microphone 2, which is situated at the midpoint of alignment 3. The data collected from microphone 2 is markedly influenced by its proximity to the barrier's edge.

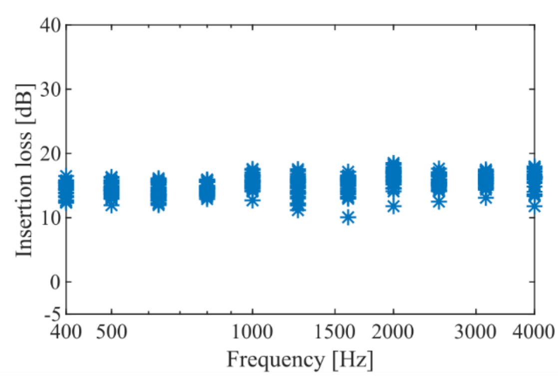

Figure 15 - Insertion loss for Microphone 3 for vehicles circulating close to the barriers.

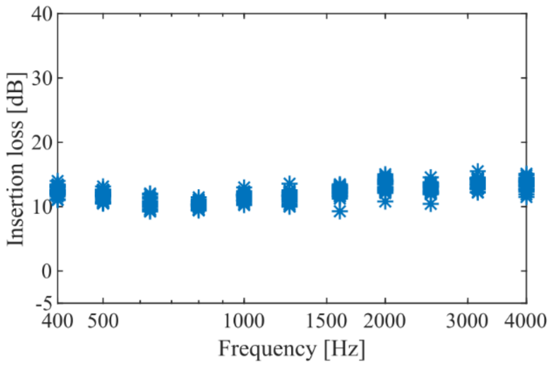

Figure 16 - Insertion loss for Microphone 2 for vehicles circulating close to the barriers.

When considering trains traveling in the opposite direction, from Lisboa to Sintra, which is farther away from the barrier, there is a noticeable reduction in Insertion Loss levels, particularly as the distance between the barrier and the track increases from 1.60 m to over 5 m. The Insertion Loss values, focusing on the same receivers examined earlier, reveals a decline in lower frequencies up to 1250 Hz (see Figure 17 and Figure 18). Within this range, IL values hover around 6 dB to 7 dB. Notably, between 500 Hz and 630 Hz, the IL values approach approximately 3 dB. Moving into higher frequencies, particularly from 1500 Hz onward, there is a rebound in IL levels, often reaching or surpassing 10 dB in certain instances. At frequency of 4000 Hz, the IL values predominantly exceed 10 dB. In the scenario of vehicles traveling at greater distances from the barrier, the distinction between the microphone situated behind alignment 3 and the microphone aligned with the catenary post becomes less pronounced. In fact, the increased distance between the barriers and the noise source seems to mitigate the impact of the shadow zone generated by the complete barrier alignment.

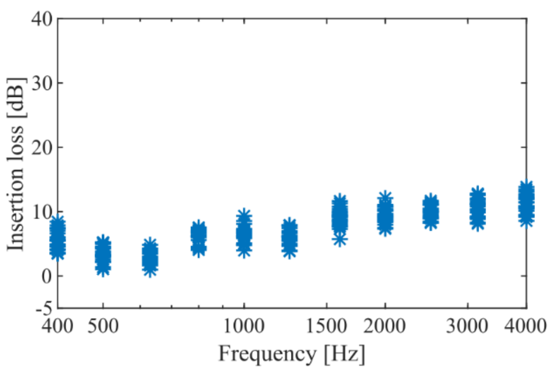

Figure 17 - Insertion loss for Microphone 3 for vehicles circulating away to the barriers.

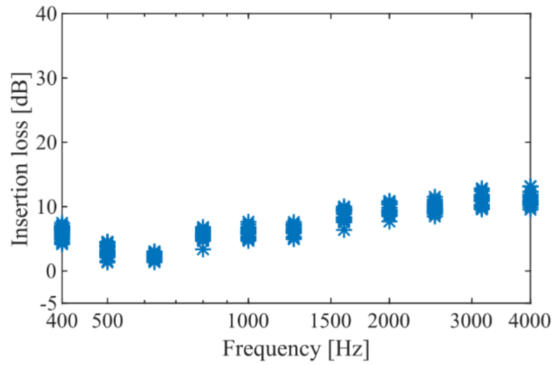

Figure 18 - Insertion loss for Microphone 2 for vehicles circulating away to the barriers.

5. COMPARISON BETWEEN NUMERICAL AND EXPERIMENTAL MODEL

The aim of this section is to compare the numerical results with the experimental railway scenario to verify and demonstrate the capability of the numerical models to predict the behavior of the acoustic barrier. For the simulation of the experimental scenario on the Sintra railway line, a 2D model was chosen.

Concerning the practical aspects of the models, the vehicle geometry was modeled as close to reality as possible, as well as the surrounding environment. It was also considered that both the barrier and the vehicle would be totally rigid, without acoustic absorption capability. For the ballast, an absorption coefficient was considered according to experimental data from reference [13]. The Figure 19 illustrates the model used on simulation.

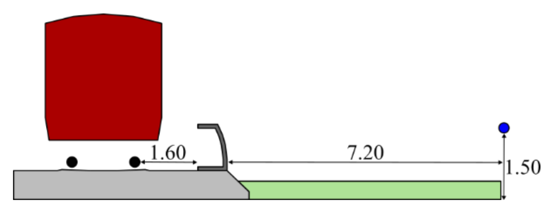

Figure 19 - Representation of the numerical model to validate the results.

Considering the various experimental records obtained, an envelope was created with the values of Insertion Loss. The numerical results do not account for local phenomena and instabilities that can affect measurements. Therefore, the numerical IL values are compared against the experimental data, expecting the numerical IL values to vary within the interval defined in the data for each one-third octave band. In Figure 20, the results of the numerical model are presented, where the train is moving close to the acoustic barrier (refer to Figure 19).

Taking into account uncontrollable conditions, local phenomena, and other external elements that impact

experimental results and cannot be numerically modeled, a very satisfactory approximation between the numerical and experimental Insertion Loss results was achieved.
For the frequency range up to 1000 Hz, the numerical IL curve aligns remarkably well with the set of experimental results. The same observation holds for the two higher one-third octave bands, i.e., 1600 Hz and 2000 Hz. However, for the one-third octave band corresponding to the frequency of 1250 Hz, a slight discrepancy is noticed. In this case, the numerical model presents a slightly higher Insertion Loss value compared to the experimental measurements.

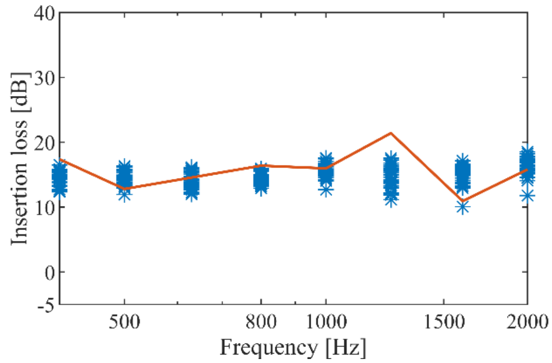

Figure 20 - Comparison between numerical results (red line) and experimental results (blue asterisks).

6. CONCLUSIONS

In this article, the development and testing of a low-height barrier specifically designed for use in railway environments was explored. Through the use of acoustic principles inherent in the ballast and railway system, has developed acoustic barrier that can effectively reduce noise levels by up to 10 dB within a frequency range of 400 Hz to 4000 Hz. The experimental results have confirmed the barrier's effectiveness, with insertion loss values exceeding 10 dB when the barrier was positioned 1.60 meters away from the track. This makes the barrier an ideal solution for reducing noise pollution in railway settings.

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