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Publication date
2024

Document Version
Final published version

Published in
Proceedings of the 30th International Congress on Sound and Vibration

Citation (APA)
Farăgău, A., van Gaal, S., Vlijm, E., Metrikine, A., Tsouvalas, A., & van Dalen, K. (2024). Mitigating Ground-borne Vibration Induced by Railway Traffic Using Metamaterials. In W. van Keulen, & J. Kok (Eds.), *Proceedings of the 30th International Congress on Sound and Vibration* Article 776 (Proceedings of the International Congress on Sound and Vibration). Society of Acoustics. https://iiav.org/content/archives_icsv_last/2024_icsv30/content/papers/papers/full_paper_776_20240416163757373.pdf

ICSV30 AMSTERDAM
8-11 JULY 2024

MITIGATING GROUND-BORNE VIBRATION INDUCED BY RAILWAY TRAFFIC USING METAMATERIALS

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The current study is concerned with ground-borne vibrations induced by railways and their impact on nearby structures and inhabitants. More specifically, it explores the efficacy of the so-called metawedge, a novel mitigation measure, in reducing ground-borne vibrations along the propagation path. A metawedge comprises a series of periodically arranged resonators along the propagation direction positioned either on the ground surface or embedded into the soil at varying depths. The difference between the metawedge and a classical locally-resonant metamaterial is that the metawedge resonators have a smooth variation of the resonance frequency with longitudinal direction. This arrangement enables the conversion of incoming Rayleigh waves into body waves, effectively channeling the energy deeper into the ground. While a theoretical proof-of-concept has been previously presented by the authors, this study makes a step forward by proposing a realizable design. Simulations indicate that a metawedge with realistic properties can significantly diminish vibration levels. Unlike conventional single trenches, which are effective only against incoming waves beyond a specific angle (outside a critical cone), the metawedge proves efficient also within this cone. This work aims to showcase the potential and feasibility of metamaterials to address present and future challenges in railway transportation.

Keywords: Ground-borne vibration mitigation, Metamaterials, Metawedge

1. Introduction

Railway transportation is attracting increased attention due to its significantly lower greenhouse gas emissions compared to other modes of transportation and its capacity for full electrification, rendering it an environmentally sustainable option. However, this growing demand has led to previously tolerable issues associated with railway transportation evolving into challenging problems that disrupt normal traffic operations. One such issue is ground-borne vibration, stemming from factors such as wheel and rail irregularities, parametric excitation caused by sleeper periodicity [1], or sudden changes in track mechanical properties, such as transition zones [2, 3, 4, 5].

Mitigation measures for ground-borne vibration encompass interventions at various levels: source (e.g., vehicle-structure interaction), receiver (such as vibration isolating foundations), and along the transmission path. This study focuses on the latter category. Among the most common mitigation measures are open (or soft in-filled) and stiff in-filled trenches [1], designed to impede wave transmission from source to receiver. The efficacy of the former approach relies on the softness of the filling material compared to the surrounding soil [6]. Experimental findings confirm its inefficiency when this condition is not met [7], necessitating open trenches in railways situated on soft soils to ensure effectiveness. However, this poses limitations regarding trench depth and sidewall stability. In contrast, the stiff in-filled trench does not face this constraint and has shown theoretical [8] and experimental [9] effectiveness. Yet, its transmission reduction is only significant above a specific angle of incidence of the incoming wave, rendering it less effective below this threshold [8]. Thus, this study aims to address the limitations of both approaches by investigating the potential of a novel mitigation measure—the metawedge [10]—to reduce ground-borne vibration at the receiver end.

The application of metamaterials in elastic media enables the manipulation of wave propagation. This concept offers novel mitigation strategies for reducing far-field vibrations generated by surface waves [10]. A metawedge consists of a series of periodically arranged resonators (of various types) along the longitudinal axis. Unlike traditional metamaterials, each resonator in a metawedge presents an offset in properties relative to others (see Fig. 1). For instance, the first resonator may rest on the soil surface, serving as a noise barrier, while the final resonator can be fully embedded. An alternative can be that all resonators are place at the ground surface, but have a smooth variation in natural frequencies. Unlike traditional measures (e.g., stiff in-filled trench), the metawedge can be effective at small incidence angles of incoming waves. Traditional metamaterials lacking the gradient in resonator properties, such as periodic geofoam-filled trenches [11] and periodic pile barriers [12], may also block wave transmission efficiently. However, in these cases, most of the energy is reflected toward the source, potentially causing a negative feedback loop (where increased vehicle vibration leads to stronger wave radiation) and increased railway track wear. In contrast, the metawedge's embedment gradient allows it to convert incoming surface waves into body waves, redirecting the energy deep into the ground. One potential drawback of this approach is that body waves may reflect at soil layer interfaces and redirect towards the receiver.

While a theoretical proof-of-concept has been previously presented by the authors [13], this study makes a step forward by proposing a realizable design, which is also the novelty of this paper. To address this, both a 2-D plane-strain model and, in contrast to most studies on the metawedge concept, a 2.5-D model are utilized. This approach allows for an exploration of the metawedge's efficiency within the conical region where the stiff in-filled trench exhibits limitations [13]. The soil is simplified as a homogeneous half-space, eliminating the aforementioned potential drawback from this analysis. While this aspect warrants further investigation in subsequent studies, the simplified soil model facilitates the initial exploration. This innovative countermeasure, where the first resonator can also serve as a noise barrier and the last one can integrate the advantages of the stiff trench, holds promise as a superior alternative to traditional countermeasures for both air- and ground-borne vibrations.

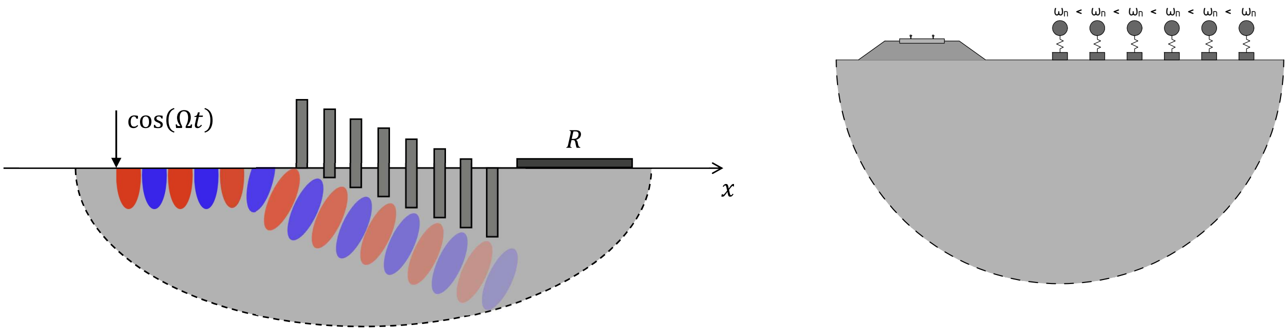

Figure 1: A schematic depiction of system considered: a harmonic load acting at the surface of a homogeneous half-space where a metawedge is placed between the source and the receiver. Left panel: the metawedge previously proposed [13] and the wave-conversion mechanism. Right panel: the metawedge design proposed in this study.

2. Model formulation and the metawedge design methodology

To evaluate the performance of the metawedge, this study employs two models: (i) a 2-D plane-strain model, illustrated in Fig. 1, and (ii) a so-called 2.5-D model, essentially a 3-D model that is uniform in the third direction (the direction of train motion). The former model is utilized for the initial design and evaluation of the metawedge, while the latter allows for an assessment of the metawedge's effectiveness against incoming waves with varying incidence angles. In both models, the soil is represented by a homogeneous half-space, and the excitation is simulated by a stationary harmonic point load, as depicted in Fig. 1. While the railway track is not explicitly modeled, its impact on quantitative results is believed to be negligible for this study.

More specifically, a unit vertical point harmonic force is applied $50\,\mathrm{m}$ from the first unit cell of the metawedge, while the receiver point is located at the soil surface 90 m from the source. The soil has mass density $\rho = 2000\,\mathrm{kg/m^3}$, shear wave velocity of 200 m/s, and Poisson's ratio $\nu = 0.25$. A very small soil damping ratio is chosen (i.e., $1\,\%$), to emphasize the metawedge performance in the absence of strong material damping.

The response of the formulated models is obtained by using a coupled boundary-element (BE), finite-element (FE), and thin-layer (TL) methods where the resonators are modelled with FE while the soil is modelled through TL and BE. The solution method is implemented in the FEMIX software (http://alvaroazevedo.com/femix/) developed by de Oliveira Barbosa and his collaborators [14]. The solution method formulation is thoroughly described in Refs. [14] and its practical potential in studying ground-borne vibration in Ref. [15].

The procedure for designing the metawedge is divided into three main stages. Firstly, the unit cell is designed as part of a structure consisting of an infinite number of identical cells, ensuring that one of its band gaps aligns with the desired frequency range. The dispersion properties of this infinite periodic structure are determined using a finite element model of a general unit cell. Secondly, the designed unit cell is incorporated into the 2-D model, where the gradient in the oscillator properties is applied. This step aims to select the gradient and number of cells required to achieve optimal mitigation. Thirdly, the designed metawedge is integrated into the 2.5-D model to examine the impact of the incident angle of the incoming wave on its performance. Iteration between these three steps may be necessary to ensure the optimal design of the metawedge.

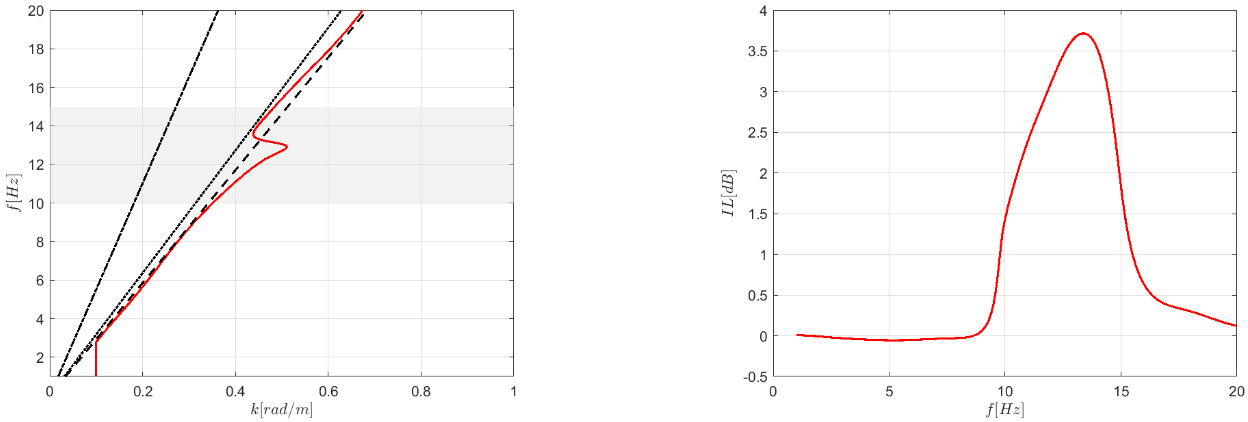

Figure 2: Left panel: Dispersion curves of the surface wave (red line) for a system with infinite number of identical unit cells ($\omega_\mathrm{n} = 13$ Hz), and the compressional (dotted line), shear (dashed line), and Rayleigh (dashed-dotted line) waves for the homogeneous half-space. Right panel: The vertical insertion loss at receiver position ($z = 0$ m and $x = 90$ m) vs excitation frequency.

3. Results and discussion

In order to propose an innovative countermeasure that is practical and effective, it is crucial to define realistic design constraints. In this study, we concentrate on ground-borne vibrations generated by typical trains in the Netherlands, without differentiation between cargo or passenger trains. Specifically, this section evaluates the efficiency and feasibility of the metawedge within the frequency range of 10–15 Hz. However, it is worth noting that metawedge design can target other frequency ranges, including very low frequencies produced by cargo trains [13].

3.1 Proposed metawedge design

The metawedge design aims for compactness to ensure the development of a structurally feasible solution that minimizes intrusion in urban settings [16]. The proposed configuration comprises 20 resonators positioned on the soil surface (refer to the right panel of Fig. 1). Each resonator has a mass of 300 kg/m, and the spring stiffness is calibrated such that the first resonator has a natural frequency of 10 Hz, gradually increasing to 15 Hz for the last resonator.

Following the design procedure outlined in Section 2, the dispersion curves of surface waves are determined and illustrated in Fig.2 for the resonator with $\omega_\mathrm{n} = 13 \times 2\pi$ rad/s. The vibration modes of the unit cell manipulate wave propagation in the medium by hybridizing with surface resonances [17]. Without the presence of resonators, the dispersion curves correspond to those of bulk and surface Rayleigh waves, represented by the straight black lines in Fig.2. However, in the presence of resonators, a band-gap is created around their natural frequencies. As the unit cell modal frequency of interest increases (i.e., the natural frequency of the resonator increases with each successive cell), the Rayleigh wave accelerates until it reaches the shear-wave velocity, at which point shear waves are excited. Essentially, surface modes with phase velocities greater than the shear-wave velocity c_S cannot exist in the elastic medium. This mechanism facilitates the transformation of surface waves into body waves that propagate deep into the ground.

3.2 Results from the 2-D model

The effectiveness of the designed system in mitigating vibrations is initially evaluated in the frequency domain, assuming plane-strain conditions. In this context, the plane wave motion is perpendicular to the metawedge. The efficiency of the mitigation measure is quantified using the insertion loss IL_i, defined as the ratio of the response in the unmitigated scenario U_i^{ref} to that in the mitigated scenario U_i. This metric is expressed by the following equation [8]:

$$\mathrm{IL}_i(x, z, \omega) = 20\log_{10}\frac{|U_i^{\mathrm{ref}}(x, z, \omega)|}{|U_i(x, z, \omega)|}, \quad i \in \{x, y, z\}. \tag{1}$$

The right panel in Fig.2 presents the vertical insertion loss IL_z at the soil surface is depicted for various excitation frequencies while Fig. 3 shows the vertical IL_z for the whole spatial domain of interest for an excitation frequency of 13 Hz. The right panel in Fig.2 provides confirmation that the designed solution effectively mitigates ground-borne vibration in the frequency range of 10–15 Hz, particularly for waves perpendicular to the metawedge. Fig. 3 shows that the metawedge reduces the ground-borne vibration in the top part of the half-space, while amplifying the response deeper in the ground. This is a clear demonstration of the wave-conversion mechanism in which surface waves are converted into body ones radiated deep into the ground. Although not shown here for brevity, the horizontal soil response exhibits a similar reduction in amplitude, despite significantly lower response amplitudes.

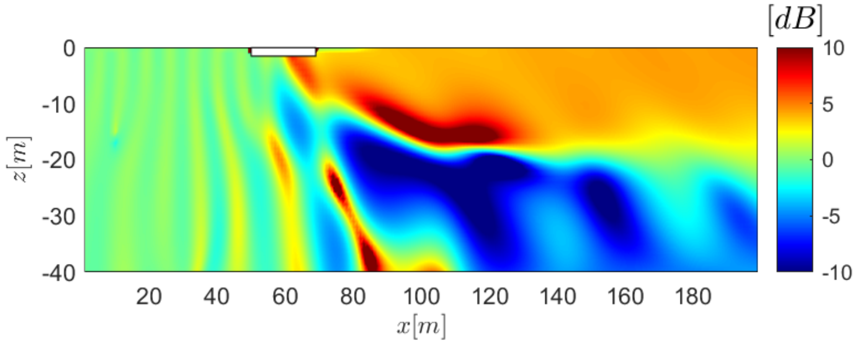

Figure 3: The vertical insertion loss in the whole spatial domain of interest for excitation frequency of 13 Hz. The white block represents the location of the metawedge.

3.3 Influence of wave incidence angle–2.5-D model

Given that waves generated by trains approach the countermeasure at various incidence angles, it is crucial to examine the impact of incidence angle on the metawedge's performance. This analysis is conducted using the 2.5-D model, and thus, the insertion loss is presented in the space-wavenumber (k_y in the y-direction)-frequency domain.

Figure 4 illustrates the vertical insertion loss IL_z for a single receiver point at the soil surface, positioned $x = 90$ m from the source. The vertical axis employs $K_y = \frac{k_y}{\omega}$ to establish the link between wavenumber k_y and the incidence angle θ, which is also displayed on the right y-axis. For small to medium incident angles (0–40 degrees), the countermeasure proves effective only for frequencies between 10–15 Hz, consistent with the findings from the previous section. For incident angles between 40–50 degrees, the metawedge seems to be effective for the whole frequency range larger than 5 Hz. This can be caused by the fact that in the 2.5-D model, the oscillators are modelled as beams in y-direction along the track; this can lead to the resonators acting as stiff trenches where the incoming wave is redirected along the beam direction. For larger incidence angles, a zone with a significant amplification appears. However, this is located at large frequencies compared to the target range. For the frequency range of interest, the insertion loss remains positive for all incidence angles.

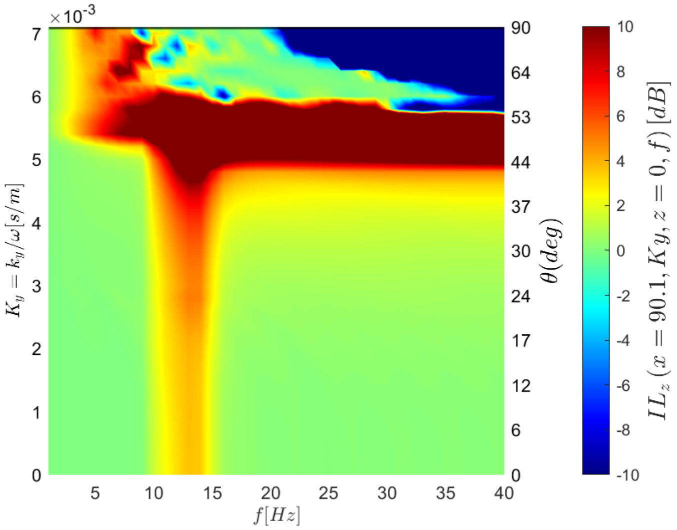

Figure 4: The vertical insertion loss vs frequency and incidence angle of the incoming wave.

Applying the inverse Fourier transform over wavenumber k_y, the soil response is expressed in the space-frequency domain. The vertical displacement field and the vertical insertion loss are plotted for an excitation frequency of 13 Hz in Fig. 5. The black bands indicate the position of the resonators. The response of the resonators is not presented here to avoid cluttering the figures.

The metawedge showcases remarkable effectiveness in dampening vibrations along the x-axis, not only within the conical region (i.e., at small incident angles) where other mitigation measures falter, but also beyond this region (i.e., at large incident angles). This attribute marks a considerable departure from traditional trench countermeasures, which generally demonstrate limited effectiveness below a specific critical incidence angle [8].

4. Conclusions

The study explores the effectiveness of a new mitigation approach, known as the metawedge, in reducing ground vibrations induced by railways. By capitalizing on the wave-mode conversion mechanism, this method converts surface waves into body waves by utilizing the unique dispersion properties of an array of resonators positioned solely on the soil surface. While a previous study by the authors [13] introduced a proof of concept, the current research proposes a feasible design for the metawedge and assesses its effectiveness in mitigating vibrations. The metawedge's efficacy is evaluated using a 2-D plane-strain model, with the soil depicted as a homogeneous half-space. Additionally, the influence of incident wave angle on the metawedge's performance is investigated using a 2.5-D model.

Results demonstrate that the proposed metawedge design can effectively attenuate vibrations in frequency ranges typical of trains (10–15 Hz). Notably, it outperforms traditional countermeasures, such as the stiff trench, particularly at small-to-medium incident angles. Finally, this work aimed to showcase the potential and feasibility of metamaterials to address present and future challenges in railway transportation.

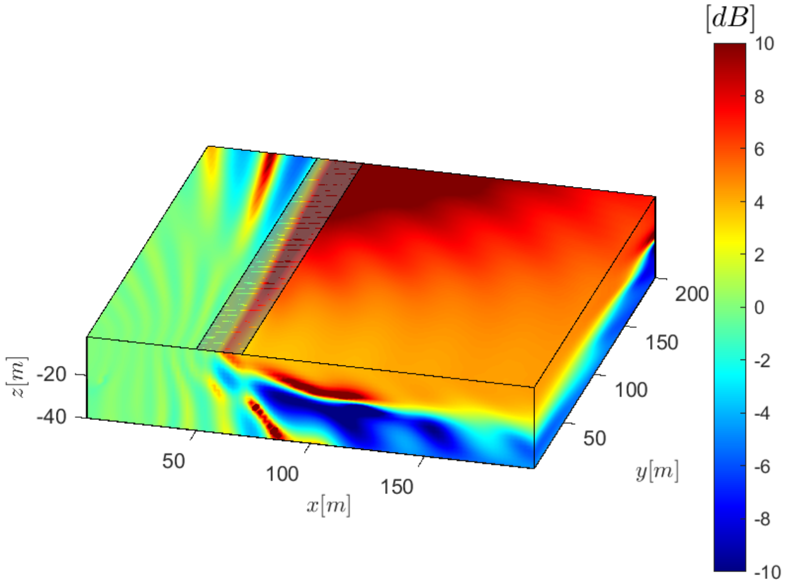

Figure 5: The vertical vertical insertion loss generated by a unit harmonic vertical point load applied at $x = y = z = 0$ with a frequency of 13 Hz.

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