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Design and analysis of a periodic metamaterial barrier for mitigating urban-induced vibrations

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ABSTRACT

Urban areas are increasingly subjected to vibrations from various sources within the urban environment. Therefore, there is an urgent necessity to find measures that can minimize their negative effects. This paper investigates the concept of metamaterial and analyzes the impact of its inclusion on the range and span of band-gaps at low frequencies (up to 80 Hz), which characterize the vibrational waves in urban areas. This is achieved by developing a finite element model of the relative unit-cell and conducting a parametric investigation on the geometrical characteristics and material properties of the inclusion. Furthermore, the depth of the embedded inclusion is examined to understand the transition of metamaterials from seismic (with the inclusion fully embedded) to resonant ones, where the inclusion is on the surface. Finally, insights are given in order to help on the selection of the correct parameters to minimize a certain range of frequencies.

1. INTRODUCTION

The growth of city population leads to an increase of the activities in urban areas, which in turns increases the negative effects of these in the daily life of the residents. One of the most important which is a serious concern for the resident is the induced vibration generated by transit system route such as rail and road traffic, or maintenance facility such as blasting, pile-driving and operating heavy earth-moving types of equipment [1-2].

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Urban-induced vibrations, the most commonly perceived type, result from the interaction between mobile systems and the earth's surface. These vibrations propagate through the ground, potentially reaching a building's foundation. Subsequently, the building reacts to these vibrations, which often manifest as oscillations in floors and walls. Ground-borne vibration typically occurs within the frequency range of 1 to 100 Hz [3]. According to ISO 14837-1 [4], it is defined as vibrations resulting from vehicle passage on rails, which propagate through either the ground or structures into adjacent buildings.

To mitigate the propagation and effects of urban-induced vibrations, researchers have investigated and developed various mitigation measures over the last few decades [5-6]. Among these measures, those utilizing the innovative concept of metamaterials are gaining increasing attention. This is attributed to the intrinsic properties of these materials, which are engineered to create a comprehensive barrier across a range of frequencies, commonly referred to as a band-gap.

This study provides an overview of the two main types of mechanical metamaterials: those with embedded inclusions (seismic metamaterials) [7] and those with inclusions at the surface (resonant or natural metamaterials) [8], illustrated in Figure 1(c) and 1(d) respectively. Then the paper discusses some applications of these two configurations of metamaterials in the context of a light railway system, assessing the level of attenuation achievable with this new type of mitigation measure. Finally, the paper then investigates the transition between these two configurations, as depicted in Figure 1(e), and examines how the depth of the embedded parts affects the dispersion within the mechanical metamaterial.

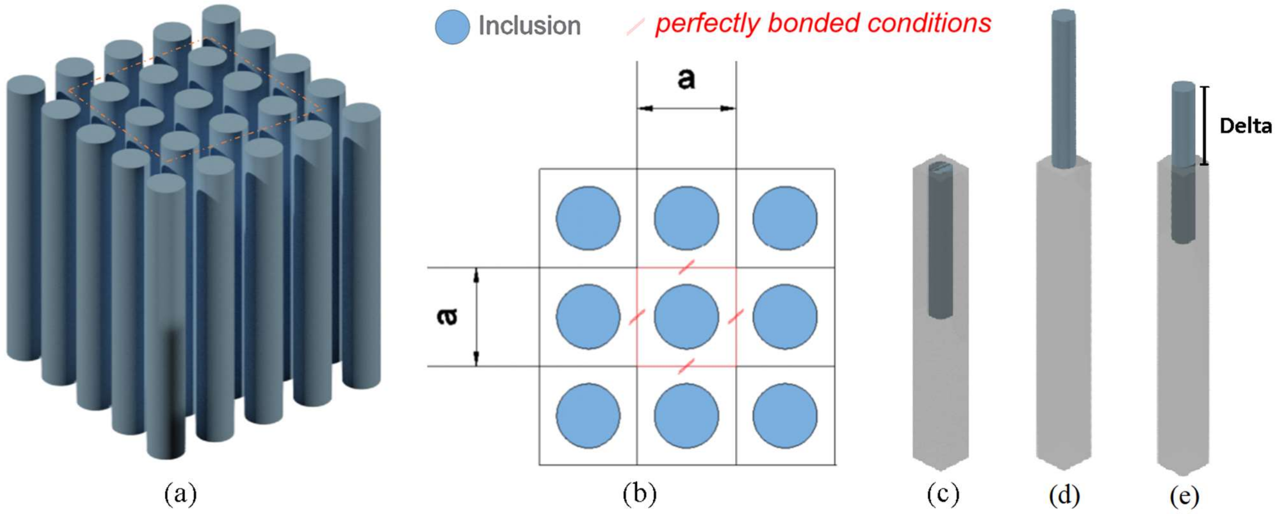


Figure 1: Graphical representation of the mechanical metamaterial (a) mechanical metamaterial 3D view, (b) mechanical metamaterial plan, (c) 3D view of the seismic metamaterial unit-cell, (d) 3D view of the resonant metamaterial unit-cell, and (e) 3D view of the transitional metamaterial unit-cell.

2. MECHANICAL METAMATERIAL CONCEPT

Mechanical metamaterials, generally referred to as periodic barriers, integrate scattering inclusions within elastic structures, exhibiting periodicity in one-, two-, or three-dimensional configurations. These structures enhance the absorption of elastic waves, contributing to seismic wave attenuation and wave-absorbing interfaces through the isolation of vibrations within specific frequency ranges, known as band-gaps. This study primarily focuses on two-dimensional mechanical metamaterials in civil engineering applications, categorizing them as seismic metamaterials when inclusions are embedded in the soil [9], and resonant (natural) metamaterials when inclusions act as resonators above the soil [10]. The investigation emphasizes a geometrical parametric approach to these mechanical metamaterials, shedding light on their attenuation capabilities while considering the utilization of cylindrical inclusions and diverse material properties.

2.1. Wave propagation in metamaterial

The wave propagation inside the metamaterial can be reduced to the unit-cell of period "a" (see Figure 1(b)) of which composes the pattern of the metamaterial structure thanks to the Floquet-Bloch theory [11]. In the case of isotropic material, the dispersion equation can be written in terms of eigenvalues, as following:

$$(\boldsymbol{K} - \omega^2 \boldsymbol{M})\, u = 0$$

where K and M are the stiffness matrix and the mass matrix, respectively. The dispersion equation provides a relation between the wave vector k and the eigenfrequency ω. Hence, to identify frequency modes, it is necessary to vary the wave vector along Γ, X, M, Γ. Therefore, to find the frequency modes, the wave vector should sweep along Γ, X, M, Γ (see Figure 2) to observe its behavior at the boundary of the first irreducible Brillouin zone. Wave vectors indicate any gaps in the frequency spectrum where corresponding frequencies are absent.

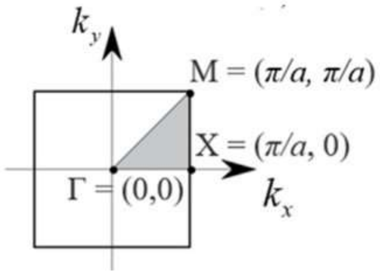


Figure 2: unit-cell on which the contour of the Brillouin irreducible zone is represented in the light grey triangle of vertices Γ, X, M.

3. METAMATERIALS RAILWAY APPLICATION

These two main configurations of mechanical metamaterials have already been investigated in the application of a light railway system, specifically using the T2000 tram operating in Brussels (as depicted in Figure 3), as a case study to assess mitigation levels [7-8]

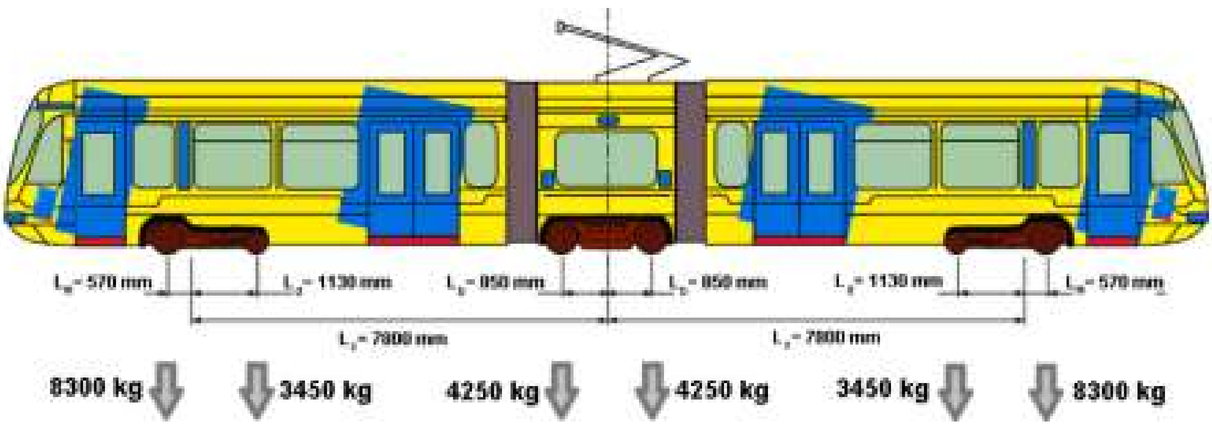
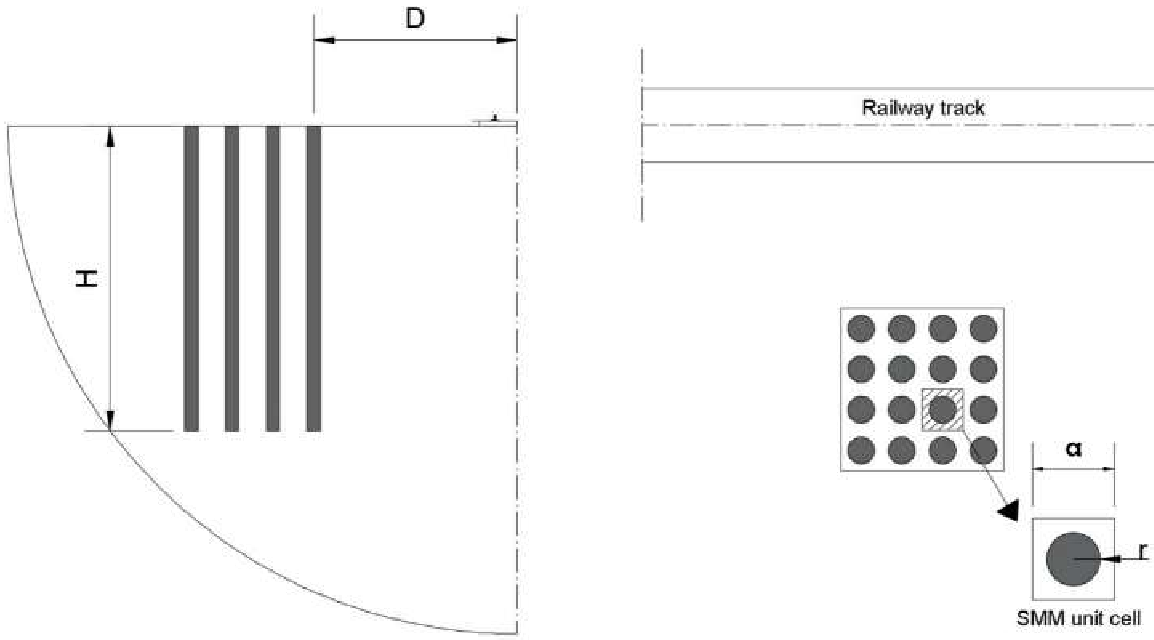


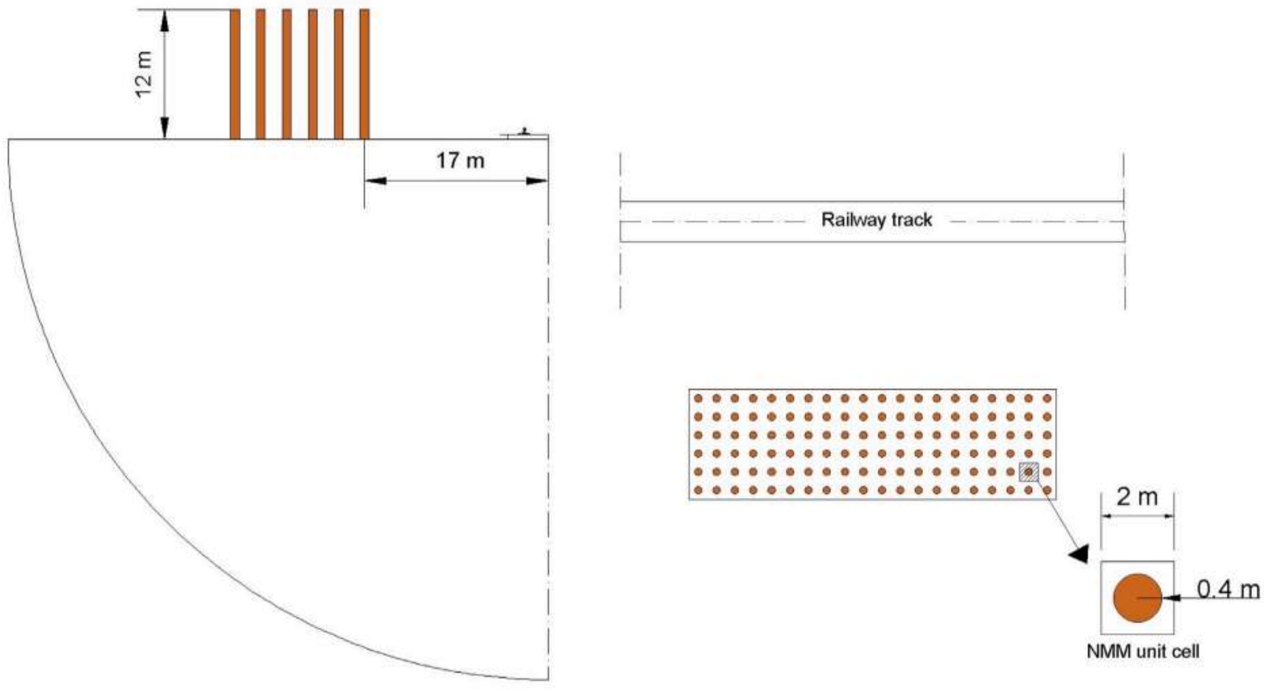
Figure 3: T2000 Brussels tram details - dimensions and axial loads.

Including a 4 by 4 group of pile embedded in the soil (seismic metamaterial – Figure 4) [7] and a 20 by 6 forest (resonant metamaterial – Figure 5) [8], the attenuation levels reported in Figure 6(a) and Figure 6(b) respectively for a tram speed of 60 [km/h].



(a) Section view (b) Bird eye view

Figure 4: Distribution of the piles in the model, with details of the seismic metamaterial units.

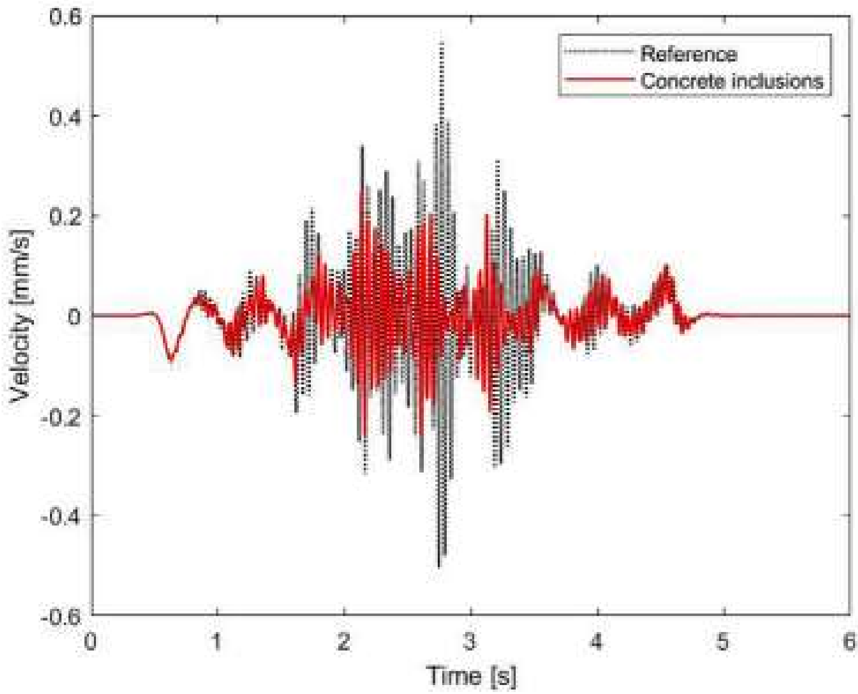


(a) Section view (b) Bird eye view

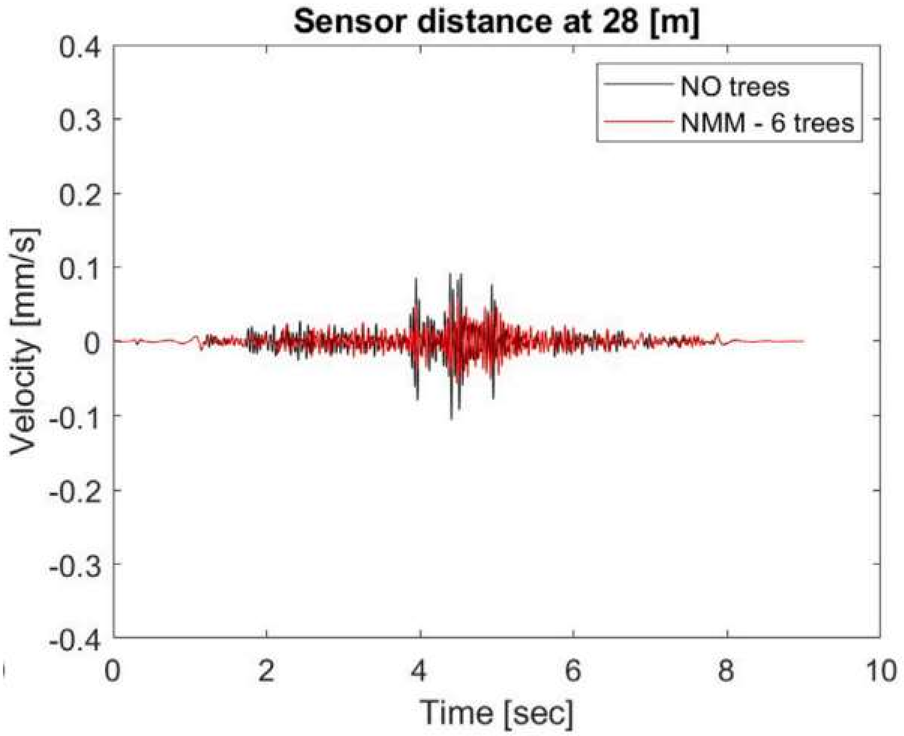
Figure 5: Distribution of the trees in the model, with details of the natural metamaterial units.

4. TRANSITION FROM SEISMIC TO RESONANT METAMATERIALS

Although the two classical configurations of mechanical metamaterials showed very good levels of attenuation, they appear to cover different frequency ranges. Therefore, it is worthwhile to examine how the depth of the inclusion embedded within the soil affects the band-gap of the specific unit-cell. Considering the geometrical and material properties reported in Table 1, Figure 7 illustrates how the position and width of the band-gaps vary with the embedded depth.



(a)



(b)

Figure 6: Vibration time history analysis of the T2000 tram: (a) at 18 m for seismic metamaterial, and (b) at 28 m for the resonant metamaterial.

Table 1: Properties of the reference unit-cell used for comparisons in the parametric study.

a [m]	r [m]	L [m]	E_{soil} [MPa]	E_{pillar} [MPa]	ν_{soil}	ν_{pillar}	ρ_{soil} [kgm^3]	ρ_{pillar} [kgm^3]
2	0.4	10	61	70000	0.13	0.2	1875	2700

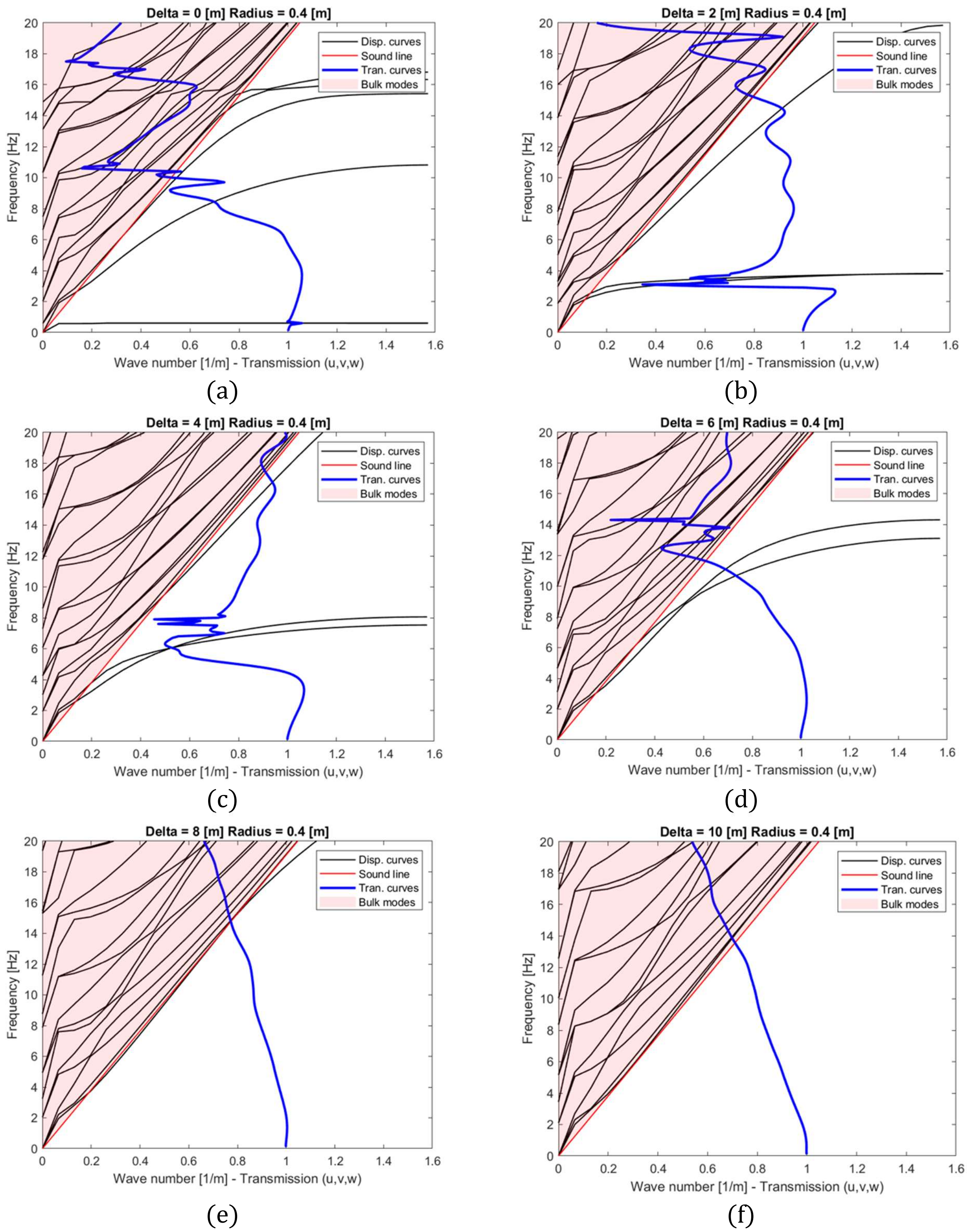


Figure 7: Dispersion curves from delta 0 to delta 10 [m].

5. CONCLUSION AND FUTURE DIRECTIONS

In this preliminary research, the issue of urban-induced vibration was addressed, and the utilization of metamaterials was explored to develop periodic barriers capable of mitigating their effects and reducing transmission levels.

The study specifically examined the application of these barriers in railway traffic, a significant source of vibration in urban areas. Previous results demonstrated the effectiveness of two standard configurations of mechanical metamaterials, namely seismic and resonant metamaterials, in attenuating vibrations and showcasing their potential for the development of new mitigation strategies. Since the attenuated frequency ranges differ between the two configurations, a parametric investigation was conducted to analyze the effect of embedding the inclusion within the hosting material.

The findings revealed that as the inclusion becomes embedded, the frequencies of the first band-gap shift to higher values, providing initial insights into the potential of exploring these and other parameters to tailor mitigation measures for specific frequency ranges and band-gap widths according to the requirements of the application.

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