PROTECTION OF STRUCTURES SUBJECT TO SEISMIC AND INDUSTRIAL VIBRATIONS USING PERIODICAL NETWORKS

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ABSTRACT The concept of frequency gaps in phononic crystals is widely used in many fields of micro and nanostructures. This article presents the findings of a numerical simulation of a concrete substratum with steel columns (pillars) coated in a polyvinyl chloride polymer (PVC). The simulation results show the existence of band gaps at medium frequencies. Exploring other metal-polymer pairs of materials such as «steel-rubber» and «Steel-Silicone», the range of band gaps has shifted towards the lower frequencies ranging from 4 to 150 m/s induced from the local resonances which cover part of the seismic frequency domain and the mechanical vibration effects on large scale structures and components. These results were improved further by notching the ends of the substratum that have the effect of widening the band gaps especially for «metal - PVC» and «metal - rubber» pairs.

I. INTRODUCTION

The phenomenon of band gaps which was previously confined only to solid state physics and semiconductors has been extended to other types of energy such as vibration or light energies (photonic crystals). More specifically, in the vibration area, research works demonstrated the existence of forbidden frequency bands, preventing the spread of certain acoustic frequencies or used as filters and oscillators in communication systems and also as acoustic isolators for resonant sensors such as gyroscopes. 1, 2-7

Recently, the study of acoustic and elastic wave propagation in phononic crystals (PC) which are considered as artificial materials constituted by a periodic repetition of inclusions in a matrix, has received a great interest. Phononic crystals so are inhomogeneous elastic media composed of one, two, or three dimensional periodic arrays o f inclusions embedded in a matrix. 8,9

Phononic Band Gaps (PBGs) can be used to realize fundamental functionalities such as mirroring, guiding, entrapment, and filtering for acoustic/elastic waves by creating defects in the Phononic Cristals (PC) structure. 10-12

The same concept of frequency band gaps in periodic materials has led to some innovative insulating phononic structures that have permitted to avoid or mitigate structural damage during an earthquake or exposure to mechanical vibrations. 13-15

However, it is a challenging task to obtain band gaps due only to the Bragg diffraction in the field of civil engineering because of the very low frequency range of the structures and the length of seismic waves. Several attempts have been made by researchers to overcome this obstacle. In this context, some works16-19 examined the potential of the local resonance phenomenon using a semi-infinite substrate on which were put up cylindrical pillars. They concluded that some dispersion came from resonance of local vibration modes. Recently, more research works were conducted on concrete foundations and buildings containing phononic networks and demonstrated the ability to block a range of seismic frequencies around 20 Hz. 20

A small scale model of a foundation block of a building made of alternated rubber layers has been studied recently.1 The authors have shown experimentally that for this particular case a range of seismic frequencies could be totally blocked or deflected.

Thin slabs with step resonators have been used to demonstrate that simultaneous effect of the local resonance phenomena and Bragg diffraction led to band gaps at low frequencies. It has also been confirmed that by varying the geometric parameters, these band gaps could be extended. 15

From this perspective, this paper proposes an isolation base for entire structures or parts of a structure such as equipments, using the properties of the periodic arrays. The base model is made of steel cylinders coated with a polymer layer (polyvinyl chloride or PVC) embedded in a concrete thin mat.

II. DESIGN OF PHONONIC STRUCTURES

The model is a square concrete mat having a thickness «t» relatively small compared to its dimensions in the plane. The mat is inlaid with columns (pillars) of circular sections coated by different materials in the embedded parts. The inner cylinders of the first basic sample are made of steel; and surrounded by a PVC layer as shown in Fig. 1(a). The basic unit in Fig. 1(b) is square having a dimension «a» equal to 1 meter; steel and PVC columns have relative radius and relative heights (r1/a ; h1/a) and (r2/a ; h2/a) respectively. Different samples are derived where the PVC is replaced by rubber and then by silicone.

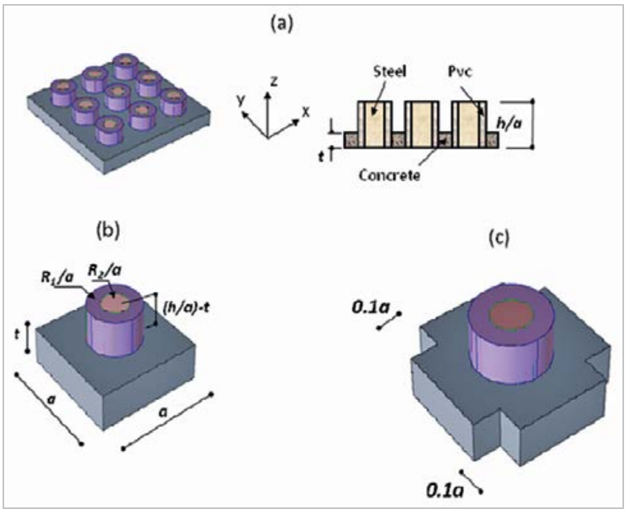

Fig. 1. Solid concrete with a periodic network consisting of steel cylinders surrounded by a layer of PVC. (a) Model of structure is assumed to be infinite in both directions x and y. (b) Basic model in first phase (before notching). (c) Basic model in third phase (after notching).

Additional samples are created by making notches at the corners of the basic units (Fig. 1(c)). The various models have been numerically studied using the finite element method (FEM). The mechanical properties of the different materials used in this study (density and elasticity coefficients) and which are considered as isotropic are given in Table I.

Table 1. *Material characteristics.*

	Density ρ (Kg/m³)	E (GPa)	ν
Concrete	2400	30	0,3
Steel	7870	209	0,3
PVC	1400	0,35	0,3
Rubber	950	0,1	0,45
Silicone	1300	0,000137	0,463

III. MODELING AND SIMULATION

The dimensions of the structure are assumed to be infinite in both directions x and y. We will focus on the simulation of a primary base cell by applying Bloch-Floquet conditions at the cell boundaries.18 The FEM simulation was performed using the Comsol Multiphysics software. The spatial meshing of the model was selected to have relatively small size elements. By varying the wave vector k in the first Brillouin zone (in ΓX, XM and MΓ directions), and solving the system of wave propagation equations, we obtain the natural frequencies of the model. For each natural frequency, the corresponding eigenvector can be deduced to show the vibrating mode in terms of the mechanical displacement field, then the frequency dispersion curves as a function of the wave vectors k can be plotted. 10,18

In the absence of external forces applied to the material, the propagation field of the two-dimensional elastic waves is given by the following equation :

$$\rho\frac{\partial^2 u_i}{\partial t^2}=C_{ijkl}\frac{\partial^2 u_l}{\partial xj\partial xk} \quad (1)$$

Where ρ is the density of the material, u_i the displacements and C_{ijkl} the elasticity constants.

The wave propagation equation can also be written in the following form :

$$\rho\frac{\partial^2 u_i}{\partial t^2}=\frac{\partial}{\partial xi}\left[\left(C_{11}-2C_{44}\right)\frac{\partial uj}{\partial xi}\right]+C_{44}\frac{\partial^2 uj}{\partial xj^2} \quad (2)$$

$C_{11} = \lambda + 2\mu$ and $C_{44} = \mu$ (λ and μ are the Lamé coefficients).
The solution according to the Bloch theory is of the form 14.

$$u_i(r,t)=e^{-i\omega t}\sum_G u_i^{K+G}(G)e^{i(K+G')r} \quad (3)$$

Where r is the position vector, ω is the angular frequency, k is the wave vector, G and G' are the reciprocal vectors.

IV. RESULTS AND DISCUSSION

For different pairs of materials, the dimensions r_1/a, r_2/a, are respectively equal to 0,45 and 0,35, h_1/a and h2/a are equal to 0,50.

The reduced frequency dispersion curves f.a (m/s) in function of the reduced wave propagation factor k.a in half of the first Brillouin zone for the material couple steel-PVC is represented in Fig. 2. The results of the first samples are illustrated in this figure, where it can be clearly noticed that a first relatively wide band gap ranges between 125 and 230 m/s and in a second higher frequency range between 250 and 350 m/s corresponding to Bragg modes. Other band gaps at a low frequency range appear between 35 and 45 m/s. We think that the low-frequency gap belongs to a resonance gap induced by the local resonance, while the higher gaps are Bragg band gaps. This result is potentially attractive for civil engineering applications. Although the band gaps remain relatively high, the effect of contrast between materials can be used to adjust the band gaps.

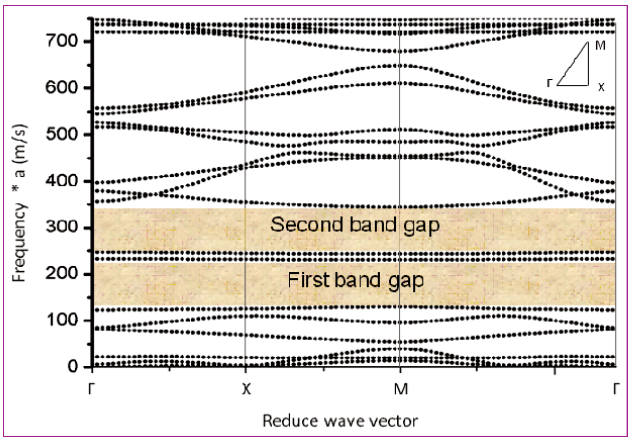

Fig. 2. *Frequency dispersion curves ($r_1/a = 0,45$; $r_2/a = 0,35$; $h_1/a = 0,5$; $h_2/a = 0,5$). Materials Used: concrete - steel - PVC (Gaps between 125 - 230 m/s and 250 - 350).*

The contrast effect of the density and elasticity between the materials used for the core and coating was underlined by many authors particularly Kushwaha et al. 21-23. Taking advantage of this contrast effect an attempt is made to reach the seismic range of frequencies, by substituting the PVC by rubber and then by silicone (Fig. 3).

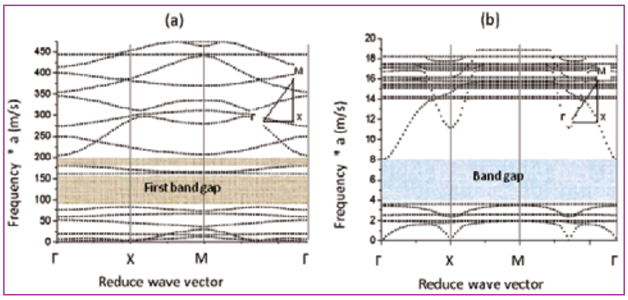

Fig. 3. Effect of density and elasticity contrast on the dispersion curves ($r_1/a = 0,45$; $r_2/a = 0,35$; $h_1/a = h_2/a = 0,5$) and parasite modes vibrations. (a) Materials used concrete - steel - rubber (Gaps between 80 - 160 m/s and 180 - 205 m/s). (b) Materials used concrete - steel - silicone (Gaps between 2 - 2,5 m/s and 3.5 - 8 m/s).

By replacing the PVC by rubber, the center of the first band gaps shifts from 177,5 to 120 m/s. However, the use of silicone shows a substantial frequency drop of band gaps because of the low elastic modulus of the silicone. In the figure 3(b), it is noted that the frequency gaps are in the spectrum of the seismic frequencies, which gives the possibility to mitigate the seismic vibrations.

Figs. 2 and 3(a) show also that the band gaps are crossed by parasite modes which unfortunately reduce the width of these bands. By analyzing the polarization of the upper bound frequency which turns about 240 and 170 m/s for figures 2 and 3(a) respectively of the band gap of the different pairs of materials, particularly the couples «steel-PVC» or «steel-rubber», it has been found that the vibration energy corresponding to these modes is concentrated at the corners of the concrete foundation as illustrated in Fig. 4. The observation of these modes shows typically deformations (in 3D) at the level of angles in phase at times, and in phase opposition at sometimes.

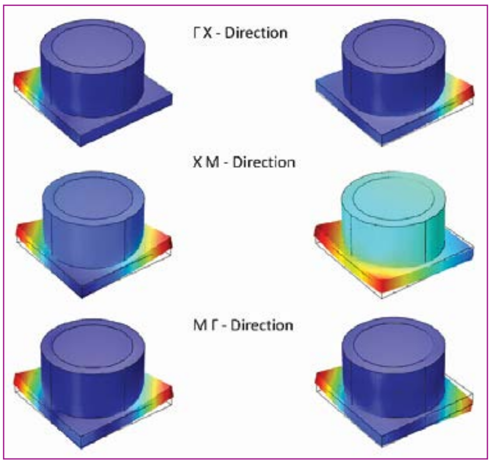

Fig. 4. Differents vibration modes in all directions of the first Brillouin zone which correspond to frequencies equal to 170 and 240 m/s.

To prevent these vibration modes, the basic model has been notched at the corners as shown in Fig. 1(c).

The frequency dispersion curves of the notched model are plotted in Fig. 5 in which it can be clearly seen that the parasite modes have disappeared and the band gaps have been expanded.

Compared to the band gaps of the initial models, a significant gain in the width of the bands has been achieved (33% for the couple « steel - PVC » and 25% for the couple « steel - rubber »); even if there is an insignificant sliding upward of the band gap for the first couple of materials.

In terms of frequencies, the final models generate band gaps between 130 and 270 m/s for steel-PVC sample and between 80 and 180 m/s for steel - rubber sample (Figs. 5(b) and 5(d)). These frequency ranges can be potentially suitable for some practical solutions to isolate the propagation of vibrations from industrial equipments.

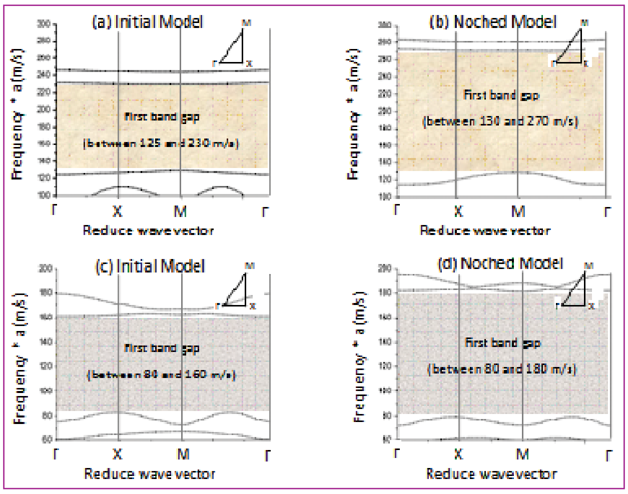

FIG. 5. Frequency dispersion curves of the notched model. (a) Materials used concrete - steel - PVC, First Phase Model (before notching). (b) Materials used concrete - steel - PVC, Third Phase Model (after notching). (c) Materials used concrete - steel - rubber, First Phase Model (before notching). (d) Materials used concrete - steel - rubber, Third Phase Model (after notching).

V. CONCLUSION

The potential of periodic networks in many fields of practical applications have been demonstrated numerically and experimentally. Because of the very low frequency range of seismic vibration, the use of this technique to mitigate the effect of earthquake vibrations is still a challenging task. In this context, a feasibility study is undertaken to investigate the efficiency in creating band gaps at low frequencies using common construction materials. Concrete blocks inlaid with steel pillars coated in PVC, rubber or silicone is used as an isolation system. Band gaps at medium and low frequencies have been achieved for some combination of materials. These band gaps have been widened by notching the corners of the basic models with PVC and rubber coating. The frequency range and the width of the obtained band gaps can be suitable for vibration mitigation of industrial equipment in civil engineering structures.

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