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Numerical investigation on sound transmission behaviour of multi-layered panels with periodic arrays of spring-mass resonators

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Abstract
Recent developments in engineering and sustainability initiatives have resulted in building trend of lightweight partitions, utilizing new materials and technologies. At the same time, noise pollution is becoming a growing problem across the globe, as a result of present-day life dynamics. The impact of the increased noise levels on human health and wellbeing is perceived. All this implies the need for sound insulation enhancement of the lightweight partitions. Theoretical and numerical investigation of multi-layered panels under acoustic excitation are conducted using different methods. The sound transmission loss (STL) of unbounded multi-layered panels is calculated using the theory of three- dimensional elasticity and well-known transfer matrix method (TMM). Additionally, the finite element method (FEM) is also used for sound transmission loss calculation and for obtaining the dispersion diagrams. Based on the dispersion curves, detection of the band gaps is made possible. In order to improve the sound transmission loss in a specific frequency region, periodic resonant units (spring-mass resonators) are tuned and introduced to the considered panels. It can be shown that the resonance mode of the spring-mass resonators couples with the plate vibration in the way of breaking the mass law and overcoming some phenomena like coincidence effect and mass-air-mass resonance. These units can be attached or embedded in the host panel. Such periodic structures recently have been recognized as acoustic metamaterials. Acoustic resonant metamaterials are artificial periodic structures with unique acoustic wave manipulation properties, owing to the dynamic influence of their local resonant units. The drawback of this concept is that this ”unordinary” power for wave manipulation works only in specific narrow frequency band associated with the resonant frequency of the resonant units. Nevertheless, this phenomenon has potential to be useful ”tool” for correcting/complementing lightweight partition systems.

Keywords: acoustic metamaterials, sound transmission loss, mass-spring resonators

1 Introduction

The scientific path of acoustic metamaterials was driven by the findings in the quantum mechanical band theory of solids, followed by the concept of photonic crystals and later the concept of phononic/sonic crystals, due to the analogy between electromagnetic and elastic waves [1], [2]. Phononic/sonic crystals are periodic scatterers incorporated in matrix/medium that interfere with acoustic travelling waves, resulting in destructive interference when Bragg’s condition is met: $n\lambda=2a\sin\theta$, where λ is the wavelength, a is the periodicity constant and θ is the incident angle of incoming wave, [3], [4]. Unfortunately, the concept of phononic/sonic crystals becomes impractical to implement in the low frequency region, where a large distance between the scatterers is required. This limitation was overcome by introduction of the dynamic effects of periodic resonant units to a host, by Z. Liu et al., [5], and the acoustic resonant metamaterials started to establish as artificial periodic structures with unique acoustic wave manipulation properties, owing to the dynamic influence of their local resonant units. The drawback of this concept is that this interesting

power for wave manipulation works only in specific narrow frequency band associated with the resonant frequency of the resonant units, [6]. Nevertheless, this phenomenon can be useful "tool" for correcting/complementing the classical systems in the region of coincidence [7], [8], [9], mass-air-mass resonance [10], [11], ring frequency [12], low-mid frequencies [13], [14], [15], [16] etc.
The possibilities and limitations of traditional materials for noise control treatment are well explored. Recent advances in technology make room for new materials with interesting properties, and thus the opportunity for more complex but smarter solutions. The concept of metamaterials is now in the scientific focus. From the extensive research in the last decade, their use for sound insulation treatment is feasible, but still, there is a vast area for exploring ahead of the researchers.
This paper is concerned with theoretical investigation of the potential of using periodically attached resonant units, with subwavelength size of the unit cell, for sound insulation enhancement of lightweight partitions i.e., gypsum walls.

2 Modelling approach

2.1 Effective mass density method (EM)

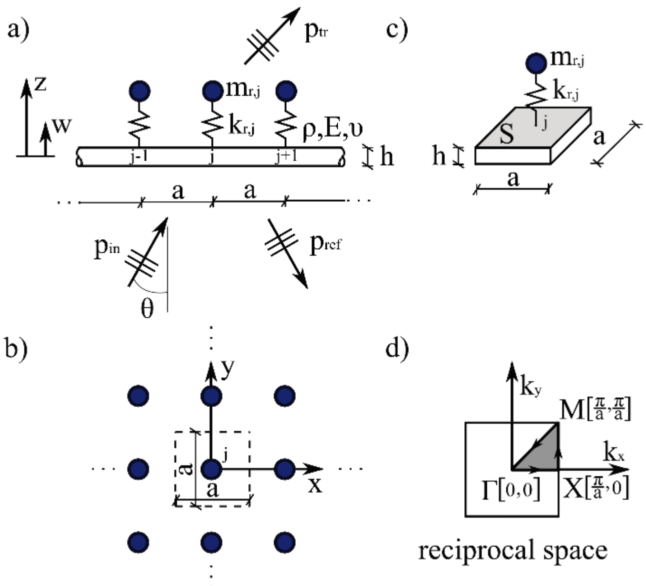


Figure 1: Metamaterial model: a) infinite thin plate with periodic resonators, b) periodic arrangement of the resonators, c) unit cell, d) reciprocal space, irreducible Brillouin zone Γ-X-M-Γ.

For elastic host plate with periodically attached single degree of freedom mass-spring units with periodicity constant much smaller than the wavelength of the motion in the plate, effective mass density representation is possible, [7]. This concept allows the use of equations derived for the host plate simply by replacing the mass density term with a frequency dependent effective mass density that incorporate the dynamic influence of the resonant units. The dynamic equivalent mass of the j-th spring-mass resonator, is given by the relation, [17]:

$$m_{eq,j} = \frac{m_{r,j}}{1-\frac{\omega^2}{\omega_{r,j}^2(1+i\eta_{r,j})}} \tag{1}$$

where $\omega_{r,j}$ is the resonance frequency of the j-th resonator, damping is introduced by complex spring constant $k_{r,j}(1+i\eta_{r,j})$, $\eta_{r,j}$ is the loss factor. By averaging the mass over the unit cell, the effective mass density is equal to:

$$\rho_{eff} = \rho + \frac{\rho_{r,j}}{1-\frac{\omega^2}{\omega_{r,j}^2(1+i\eta_{r,j})}} \quad (2)$$

2.2 Transfer matrix method (TMM)

For modelling the unbounded multi-layered systems, transfer matrix method is used. Based on the theory of elasticity and Biot's theory, 4x4 transfer matrix for elastic-solid layer and 6x6 transfer matrix for elastic-porous layers are given in [18], and for orthotropic solid layer is 6x6, [19],[20]. The transfer matrix for stationary fluid layer is 4x4. The derived transfer matrices relate acoustic pressure and particle velocity on both sides of a layer considering plane wave propagation. The fluids on both sides of the partition are semi-infinite. The continuity conditions between two adjacent layers are used to build the global transfer matrix. From this, the reflection and transmission coefficient can be easily calculated hence the sound transmission loss. For diffuse sound field, where the waves are incident from all direction with equal probability, the sound transmission coefficient can be obtained through integration:

$$STL_d = -10log_{10}\frac{\int_0^{2\pi}[\int_0^{\pi/2}\tau(\theta,\phi)sin\theta cos\theta d\theta]d\phi}{\int_0^{2\pi}[\int_0^{\pi/2}sin\theta cos\theta d\theta]d\phi} \quad (3)$$

2.3 Finite element method (FEM)

For comparison and expanded analysis, finite element method will be used for calculation of the sound transmission loss (STL) and dispersion diagrams. By using simple 1D model of infinite panel and 3D model of finite panel, sound transmission loss is obtained. Perfectly matched layers are employed for terminating the infinite domains, Figure 2. Diffuse field is modelled as pressure load (incident + reflected) calculated as a sum of N random plane waves (random angles of incidence and phases) multiply by 1/sqrt(N). Band diagrams i.e., dispersion diagrams are calculated using 3D FEM model of the unit cell by setting periodic boundary conditions based on Floquet-Bloch theory. In order to obtain the band structures, it is sufficiently to sweep the k-vector through the contour of the irreducible Brillouin zone Γ-X-M-Γ, Figure 1. The main characteristic of the acoustic resonant metamaterials is their ability of creating stop bands - that is frequency range where no free propagation of waves exists. These stop bands can be easily detected via dispersion diagrams. Periodic boundary conditions are employed for the 1D FEM model as well.

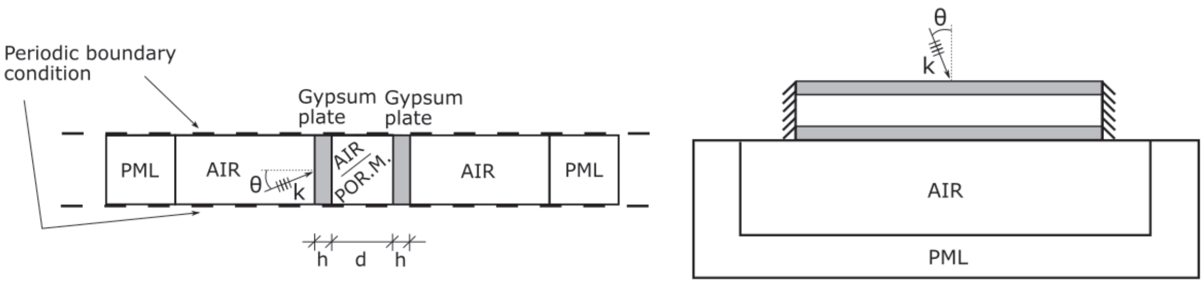


Figure 2: 1D FEM model (left) and plane section of 3D FEM model (right) for calculation of sound transmission loss.

2.4 Problem description

The potential of metamaterial concept with attached resonators for sound insulation will be discussed through gypsum walls. Single gypsum panel GP and double-leaf gypsum wall, without cavity absorption, GW1, and with cavity absorption, GW2, will be considered, Figure 3. Material properties of the walls are given in

Table 1. The panels are analyzed without and with periodically attached single degree of freedom mass-spring resonators, incorporated in the models via effective mass density EM. When considering the sound transmission loss of single and double panels, the main "weak spots" are the coincidence region and mass-air-mass resonance. The target of this research is to analysis the possibility of "correcting" these weaknesses.

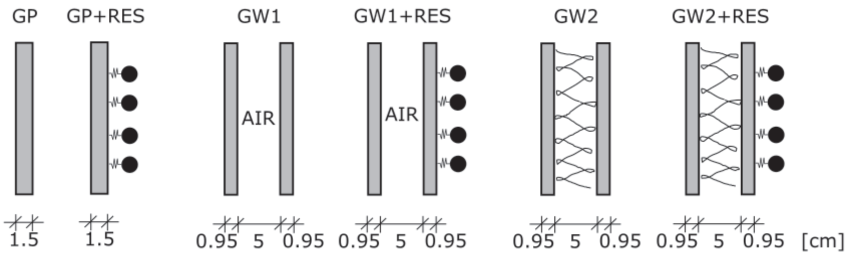


Figure 3: Configuration of considered panels.

Table 1: Material properties

	GP	GW1		GW2		
		Gypsum panels	Air cavity	Gypsum panels	Porous material: Properties of the solid elastic frame	Porous material: Air saturated pore - fluid properties
Density [kg/m3]	850	700	1.2	700	30	1.2
Modulus of elasticity [GPa]	4.1	2.25		2.25		
Poisson's ratio	0.3	0.3		0.3	0.3	
Flow resistivity [Ns/m^4]					6000	
Porosity					0.98	
Tortuosity					1.06	
Viscous dimension [µm]					150	
Thermal dimension [µm]					300	

3 Results and discussion

For GP, GW1 and GW2, single degree spring-mass resonators are selected to be attached periodically. The mass of the resonators m_r provides mass addition of $m_r/(\rho ha\text{^}2)=0.5$, i.e., *50%,* while the stiffness of the spring is tuned in order to obtain the desired resonant frequency. The loss factor for the resonators is set to be 10%. The panels are exposed to oblique and diffuse incidence.

The sound transmission loss for oblique incidence, $\theta=60°$, for bare GP and GP with attached resonators with different resonant frequencies is shown in Figure 4a. From the STL curve of the bare GP, the classical behaviour of a single panel can be observed. The mass law is "interrupted" by the coincidence dip, determined by the critical frequency, fc. When the resonators are introduced, picks/dips occur in the sound transmission loss. If the resonant frequency of the resonators is way below the coincidence dip, one sharp pick exists, then one sharp dip, followed by the coincidence dip. But if the resonant frequency is set to be in the coincidence dip, dominant role has the pick and depending on the position of the pick, the coincidence dip is more or less controlled. In Figure 4b, the comparison between TMM and 1D FEM infinite model is shown. The curves match perfectly. Here the resonators are tuned to the critical frequency of the host panel. For the frequencies before the resonant frequency of the resonators, there is improvement in the mass law region due to the additional weight from the resonators, but for the frequencies after the resonator effect, the curve approaches the curve of the bare panel.

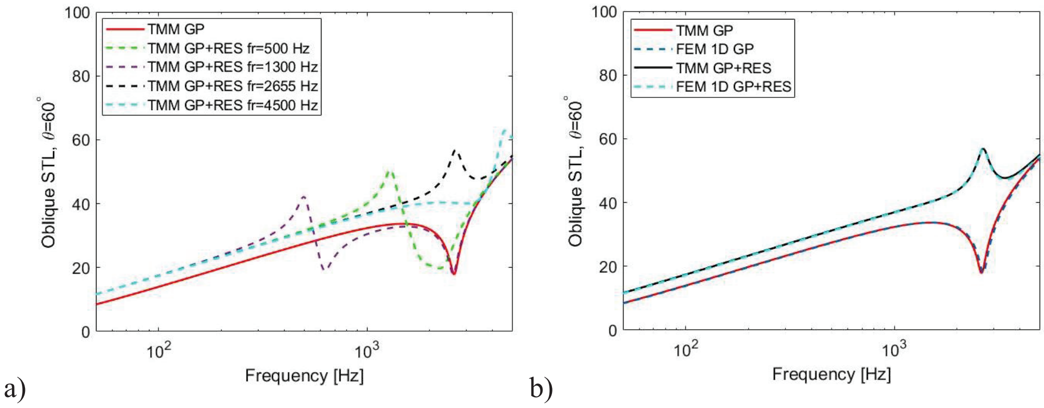


Figure 4: STL for oblique incidence of GP without and with periodically attached resonators.

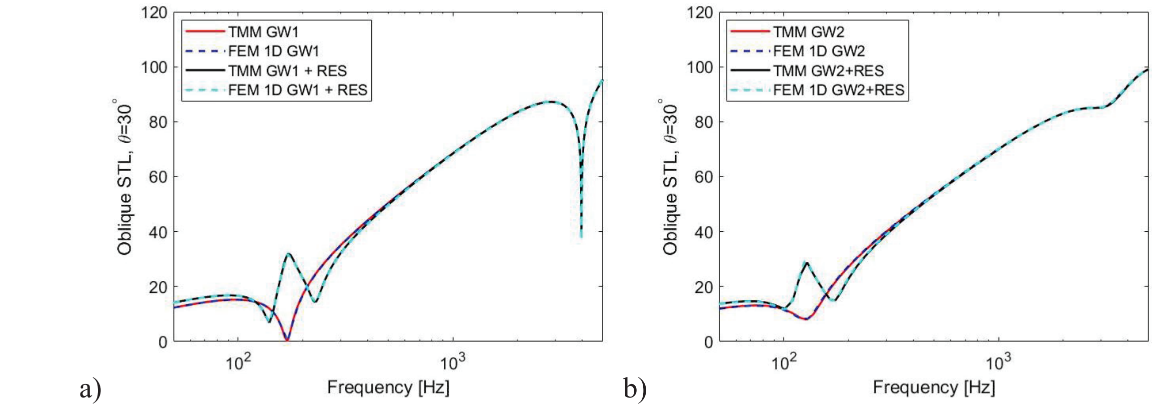


Figure 5: STL for oblique incidence of GW1 and GW2 without and with periodically attached resonators.

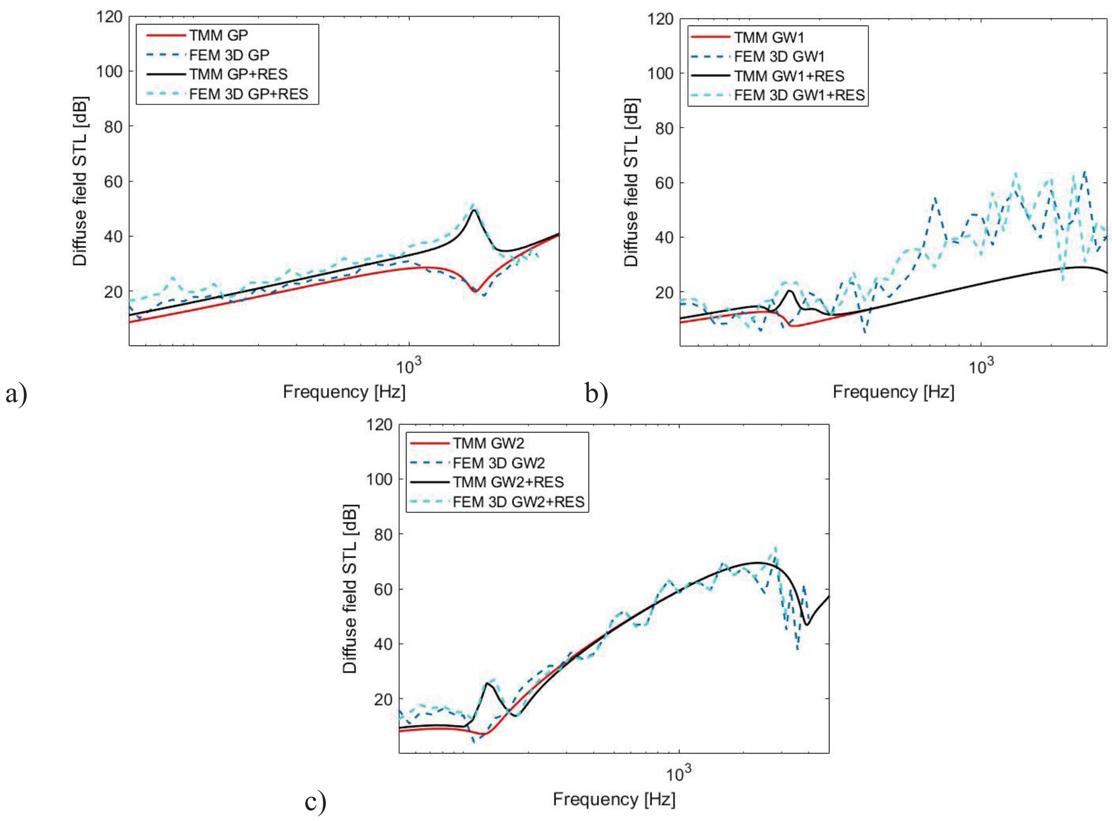


Figure 6: STL for diffuse incidence of GP, GW1 & GW2 without and with periodically attached resonators.

In Figure 5, the STL curves for GW1 and GW2 for oblique incidence, $\theta=30°$, without and with periodically attached resonators are presented. Here the characteristic behaviour of double walls under acoustic excitation is evident, where besides the mass law region and coincidence dip, mass-air-mass resonance occurs. The resonators are tuned to the mass-air-mass resonance and the improvement is evident. For the solid-porous-solid GW2 wall, in the TMM model, very thin fluid layer is introduced between layers. The 1D model and TMM results are in agreement.
For diffuse field, the STL calculation based on the finite 3D FEM model shows good agreement with the infinite TMM model, for GP and GW2, Figure 6. There are some discrepancies in the low frequency region because of the finite dimensions of the panel in the 3D FEM model. For GW1 there is significant difference regarding the impact of the infiniteness of the air layer to the coupling between the plates in the TMM model.
Materialization of one resonator targeting the critical frequency of GP is proposed. This solution also applies to double wall with GP panels. The resonator is composed of steel mass and PLA 3D printed base. The resonators are attached to the plate in periodic schemes with periodicity constant $a=6$ *cm*. Mass addition is set to be 50% (of the host plate) and the stiffness is controlled through the PLA base. For the bare panel it is obvious that no band gap exists, but for the metamaterial design, band gap with width of nearly 250 Hz appears, between 1900-2150 Hz. These results shows that by tunning the dynamic behaviour, a favourable interaction between resonators and bending wave in host plate is possible, resulting in band gap creation, Figure 7.

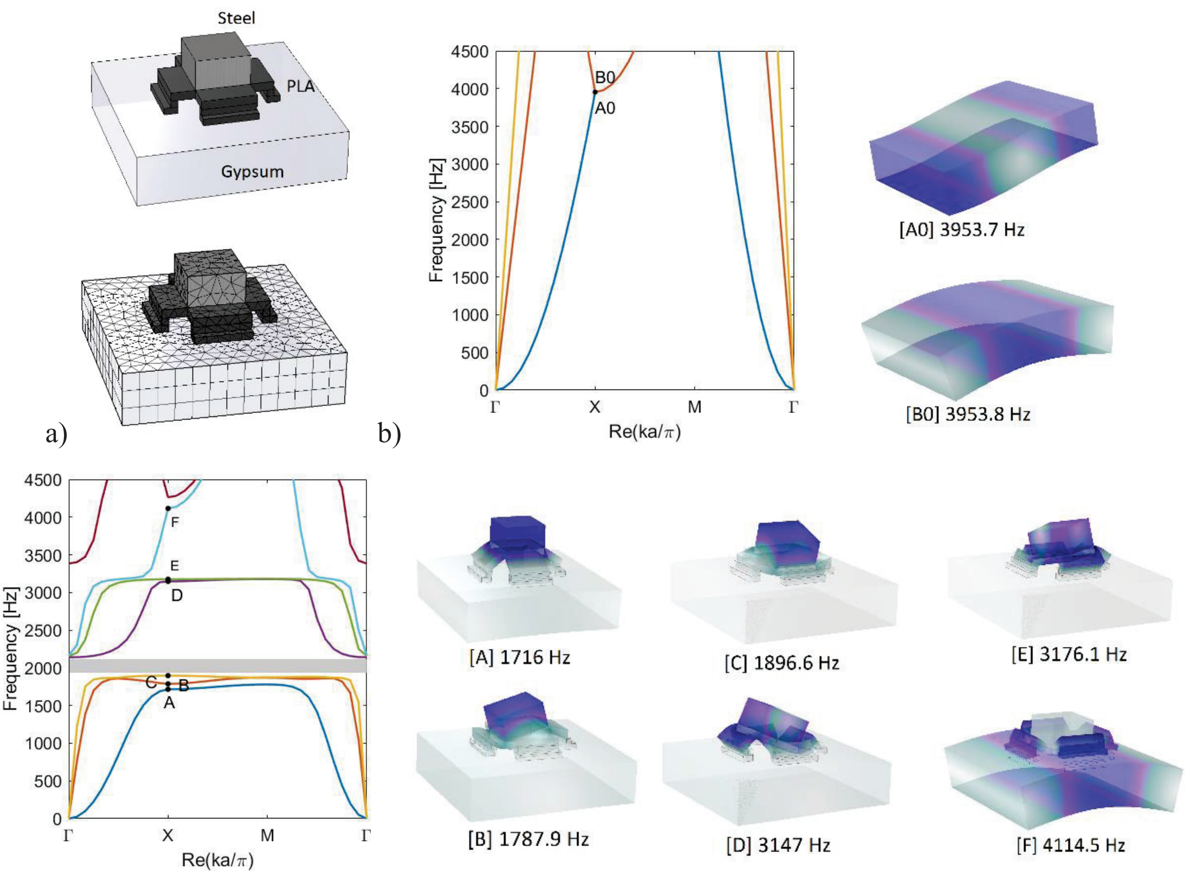


Figure 7: a) Materialized resonator targeting the critical frequency of GP, dispersion diagrams for b) bare plate and c) plate with resonators.

The proposed gypsum plate with resonators from Figure 7, is used to build a double wall, with cavity absorption, 15mm(50mm)15mm. The resonators are attached on both panels. Using the information provided in the dispersion diagrams as input for the TMM model with effective mass density, the STL behaviour is predicted, Figure 8.

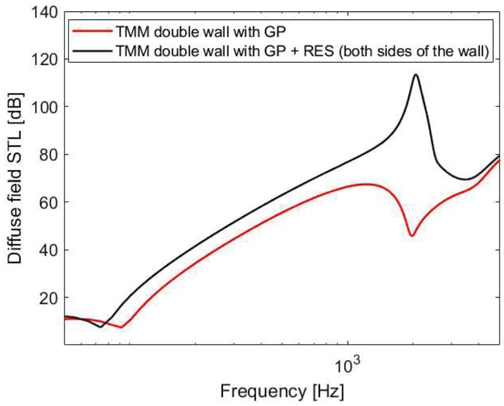
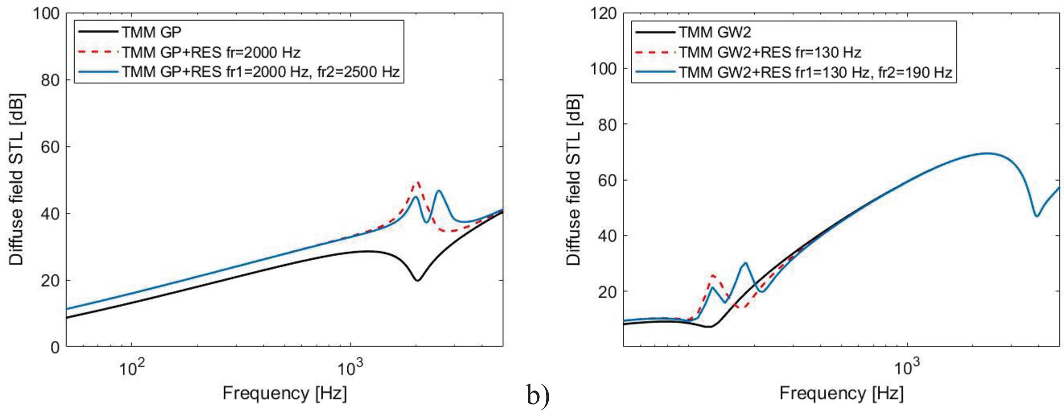


Figure 8: Double wall 15(50)15 with proposed resonators applied on both panels.

The main drawback of this concept is that the positive effect is in the narrow frequency region. One possible improvement is to introduce two or more resonators in one unit cell that have slightly different resonant frequencies, that can create two or more consecutive picks in the STL curve, Figure 9.



a) b)

Figure 9: Two mass-spring resonators in one unite cell for GP and GW2.

4 Conclusions

With introduction of periodic mass-spring resonators to a lightweight partition, with proper design, improvements in the specific regions like coincidence region or mass-spring mass resonance can be obtained. Steel-PLA resonators can be one possible solution for materialization. By tunning the dynamic behaviour of the resonant unit, a favourable interaction between resonators and bending wave in host plate is possible resulting in band gap creation. Of course, there are many drawbacks of this concept, like, the effectiveness is only in narrow frequency range, also if the design of the resonant units is not precise, significant dips can arise, then, complicated design of the panels etc. But new technologies, like 3D printing, open the door for the metamaterials, also the intense research in this area directed towards optimization of the width of the band gaps, for example by introducing tailored different resonant units in one unit cell. In that way, metamaterial design can offer possible solution for noise treatment.

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