Numerical Study of Plate-type Acoustic Metamaterial Panels Made of Sustainable Materials

Felix Langfeldt*, Yuan Sim, Jordan Cheer
Institute of Sound and Vibration Research, University of Southampton, Southampton, SO17 1BJ, United Kingdom
* *E-mail: F.Langfeldt@soton.ac.uk*

Introduction

The field of acoustic metamaterials has emerged as a potential source of new technologies for creating lightweight and compact acoustic partitions to reduce noise, especially in the challenging low-frequency regime. Plate-type acoustic metamaterials (PAM) are a particular acoustic metamaterial design consisting of a thin baseplate with periodically attached masses. Although PAM can be very lightweight and thin, they can have sound transmission loss (STL) values that considerably exceed the corresponding mass-law STL. Thus, panels with PAM can be an effective means to tackle low-frequency tonal noise with a minimum additional mass, for example in aircraft with propeller engines. Previous investigations have shown that by stacking two (or more) PAM layers, the typically narrow bandwidth of the individual PAM layers can be extended to make PAM panels applicable to more than just noise sources with fixed tonal frequencies [1].

In almost all previous studies involving PAM, the materials used for manufacturing the PAM were mineral-oil based materials (e.g. polyethylene terephthalate, PET [2]) or metals [1]. Such materials have a high CO2 footprint in manufacturing and are difficult to recycle. The use of sustainable materials in acoustics (such as cork or plant fibres) has gained attraction in recent years [3]. For example, Ciaburro and Iannace [4] studied the sound absorption of PAM with cork as the baseplate material and reused drawing pins or buttons as masses. Building PAM panels out of sustainable materials would clearly improve the carbon footprint of these sound insulating structures. However, it has not yet been investigated if the sound insulation performance of PAM panels made from conventional materials can actually be replicated exclusively using sustainable materials.

Based on the context outlined above, the main research question of this work is: Can sustainable materials be used to manufacture PAM panels with the same noise insulation characteristics as PAM panels made of conventional materials? The present work is structured as follows: First, the optimization procedure to design PAM panels made of sustainable materials is described and the resulting PAM panel designs are discussed. Then, the diffuse sound transmission loss of these optimized PAM panel designs with additional porous sound absorbing material is compared to that of a PAM panel made of conventional materials.

PAM Optimization

Basic PAM panel design

The basic design of the PAM panels that will be considered in this work consists of two PAM layers separated by an air gap of thickness H which is partially filled with a porous material. Each PAM layer consists of a baseplate (thickness h_b) and periodically added strip-shaped masses, which are characterized by a mass thickness (h_M1 for the first PAM, and h_M2 for the second) and the spacing between the mass strips (l_1 and l_2). The unit cell width a is the same for both PAM layers. The use of strip-shaped masses (instead of, e.g., circular masses) simplifies the manufacturing of the PAM layers significantly and does not have any adverse effects on the sound reduction behavior of the PAM [2].

Numerical model

A finite element model (FEM) of a single unit cell of the double-layer PAM with strip masses was generated to calculate the STL of different configurations during the optimizations. Choosing PAM with strip masses enabled the use of a 2D model in the simulations, significantly speeding up computation times [2]. The general setup, boundary conditions, and mesh of the numerical model are shown in Fig. 1. It should be noted that the lateral boundaries of the computational domain were periodic boundary conditions to allow the computation of the oblique incidence STL with a plane wave incidence angle θ_0. The top and bottom boundaries were non-reflecting.

Optimization problem statement

Since the vibro-acoustic properties of the PAM are governed by the material properties and the unit cell geometry simultaneously, changing the material of a PAM panel will also result in different geometrical parameters, if the anti-resonance frequencies and bandwidth of the PAM panel are supposed to remain unaltered. Here, an optimization procedure is used to identify the geometrical design parameters of a PAM for a given set of material combinations for the PAM baseplates and masses. This optimization problem can be formulated as follows:

$$
\begin{aligned}
\underset{a,\frac{l_1}{a},\frac{l_2}{a},h_\mathrm{M1},h_\mathrm{M1},h_\mathrm{b}}{\text{maximize}} \quad & \sum_i \min(\mathrm{TL}_0(f_i) - \mathrm{TL}_{0,\mathrm{ref}}(f_i), 6\,\mathrm{dB}) \\
\text{subject to} \quad & a \in [10\,\mathrm{mm},100\,\mathrm{mm}] \\
& \frac{l_1}{a} \text{ and } \frac{l_2}{a} \in [0.1,0.9] \\
& h_\mathrm{M1} \text{ and } h_\mathrm{M2} \in [1\,\mathrm{mm},20\,\mathrm{mm}] \\
& h_\mathrm{b} \in [h_\mathrm{b,min},h_\mathrm{b,max}]\,.
\end{aligned}
$$

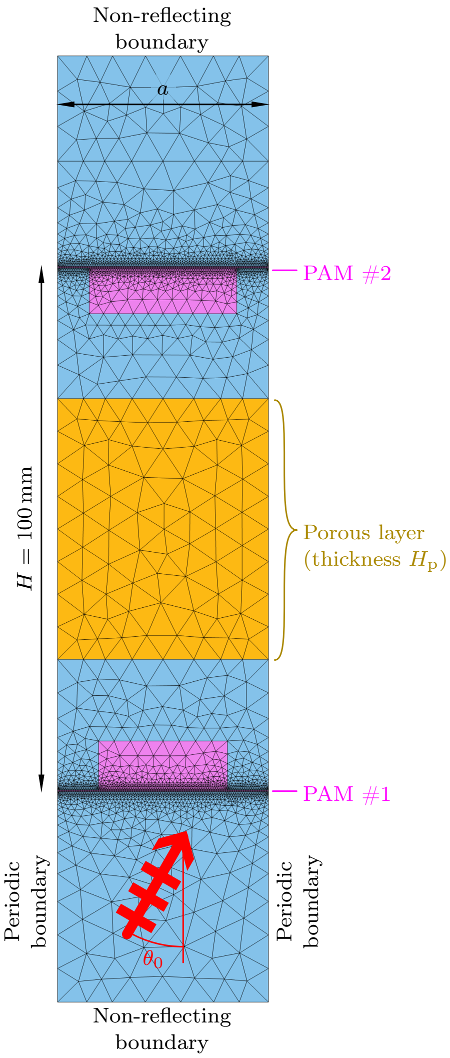

Figure 1: Finite element model of the PAM panel used to calculate the STL.

The objective function aims to maximize the normal incidence STL difference, summed over all frequency points f_i within the optimization frequency band 200 Hz to 400 Hz. The STL difference is computed using the normal incidence STL of the double-layer PAM TL_0 (obtained using the numerical model) and a reference STL value $\mathrm{TL}_{0,\mathrm{ref}} = \max(\mathrm{TL}_{0,\mathrm{wall}}, \mathrm{TL}_{0,\mathrm{dwall}})$, consisting of the maximum of the normal incidence STL of a mass-equivalent homogeneous single wall and that of a double wall with the same wall spacing H and m''_tot equally distributed on both walls. The STL difference is cut off at a maximum value of 6 dB to penalize very high STL differences in a very narrow frequency band. This ensured that the optimization converges towards broadband STL improvements instead of favouring PAM designs exhibiting a single narrowband peak with very large STL values. The total surface mass density m''_tot of the optimized PAM panel designs was constrained to be equal to $2\,\mathrm{kg/m^2}$ in all cases. The minimum baseplate thickness was $h_{\mathrm{b,min}} = 50\,\mathrm{\mu m}$, except for the cork based PAM, where $h_{\mathrm{b,min}} = 0.5\,\mathrm{mm}$ was chosen, because of manufacturing limitations. The maximum baseplate thickness was given by $h_{\mathrm{b,max}} = 0.5 m''_\mathrm{tot}/(2\rho_\mathrm{b})$ to ensure that at most 50 % of the total surface mass density is used up by the baseplates.

The optimization problem was solved using the Nelder-Mead algorithm [5]. To increase the probability that the algorithm identified the global optimum, each optimization was performed 20 times with random initial values for the design parameters, sampled from the feasible set. Of these 20 optimizations, the design parameter set leading to the highest objective function value was chosen as the final optimization result.

Optimization results

The optimizations have been performed for three PAM material combinations: (1) PET (baseplates) and PVC-F (masses), as in Ref. [2]; (2) Cork (baseplates and masses); (3) Paper (baseplates) and Bamboo (masses). Table 1 provides the material parameters used in the simulations. The resulting optimized PAM parameters are listed in Table 2. Additionally, Fig. 2 shows a scale illustration of all three optimized PAM unit cells. The main result of this optimization is that it is possible with all three material combinations to achieve the same objective function value. Thus, for the given optimization setup, using sustainable materials for the PAM does not negatively impact the acoustic performance. By comparing the numbers in Table 2 and looking at the unit cells in Fig. 2 it can be noticed that the unit cell designs with sustainable materials are larger compared to the design using PET/PVC-F. This is particularly evident for the PAM panel using cork, where the strip masses are considerably

Table 1: PAM material parameters used in the simulations.

Material	ρ	E	ν	η	
PET	1400	3.5	0.4	5	[2]
PVC-F	460	1.2	0.4	5	[2]
Cork	160	0.02	0.01	5	[6]
Paper	750	3	0.3	5	[7]
Bamboo	660	9	0.4	5	[8]
	$\frac{\mathrm{kg}}{\mathrm{m}^3}$	GPa	—	%	

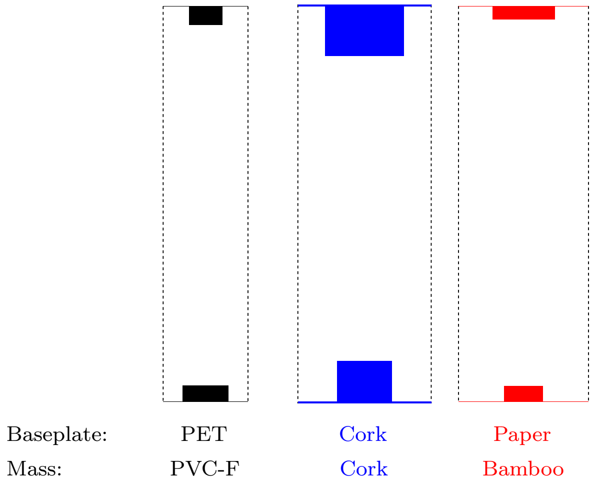

Figure 2: Illustration of the unit cells of the optimized double-layer PAM designs given in Table 2 (to scale).

Table 2: Optimized parameters of the PAM layers.

Materials								
Baseplate	Mass	a	$\frac{l_1}{a}$	$\frac{l_2}{a}$	h_{M1}	h_{M2}	h_{b}	Objective
PET	PVC-F	21.50	0.46	0.61	4.04	4.70	0.05	186
Cork	Cork	33.80	0.59	0.41	10.23	12.55	0.50	186
Paper	Bamboo	32.95	0.70	0.52	3.88	3.32	0.12	186
		mm	—	—	mm	mm	mm	dB

thicker. This can be attributed to the low density of cork, requiring larger thicknesses to achieve the target surface mass density of 2 kg/m^2.

The normal incidence STL for the three optimized PAM panel designs is shown in Fig. 3. All three PAM panel configurations exhibit the same characteristic features: Two anti-resonances can be seen with one anti-resonance frequency being close to the lower limiting frequency of the optimization interval, and the other anti-resonance frequency being slightly lower than the higher limiting frequency. This results in a “plateau” forming between two anti-resonances with an STL improvement of at least 6 dB compared to the two reference curves. At higher frequencies, however, the STL drops significantly, due to the decoupling of the mass and the baseplate. The three material combinations lead to almost equal STL spectra, indicating again that the use of sustainable materials is not reducing the acoustic performance of the metamaterial panels.

Diffuse transmission loss

To investigate the performance of the optimized PAM panels under conditions which are more representative of real-world acoustic excitations than normal incidence, additional simulations to calculate the diffuse incidence STL of the optimized PAM panels have been performed. This was done by simulating the STL for multiple incidence angles between $\theta_0 = 0°$ to $78°$ and integrating the resulting STL values over this frequency range [2].

Since the addition of sound absorbing material in the air gap between two plates significantly improves the STL at diffuse incidence [9], a layer of porous material was added to the optimized PAM panels in these simulations. The porous layer was modelled using the Johnson-Champoux-Allard equivalent fluid model (limp formulation) [10] with the material properties given in Table 3. In case of the PAM panel using PET/PVC-F, rock wool was used as the porous material. For the two PAM panels made of sustainable materials, hemp fibres were chosen. From Table 3 it is evident that the density of both porous materials is different. To keep the mass of all three PAM panels the same, the thickness of each porous layer was adjusted accordingly: For rock wool, the porous layer thickness was 50 mm, and for hemp 74 mm.

The resulting diffuse incidence STL values are shown in Fig. 4. The grey curve corresponds to a double wall with homogeneous plates, filled with a layer of rock wool, and the same overall thickness and mass as the PAM panels. The results in Fig. 4 show that all three PAM panel configurations have a similar STL improvement between 200 and 400 Hz, as in the normal incidence excitation case. This indicates that even though the PAM unit cell geometries have been optimized under normal incidence, their

Table 3: Porous material parameters used in the simulations.

	Rock wool [10]	Hemp [11]	
Density	130	88	$\frac{\mathrm{kg}}{\mathrm{m}^3}$
Porosity	94	93	%
Flow resistivity	135	12.5	$\frac{\mathrm{kN\,s}}{\mathrm{m}^4}$
Tortuosity	2.1	1.05	—
Viscous char. length	49	50	µm
Thermal char. length	166	109	µm

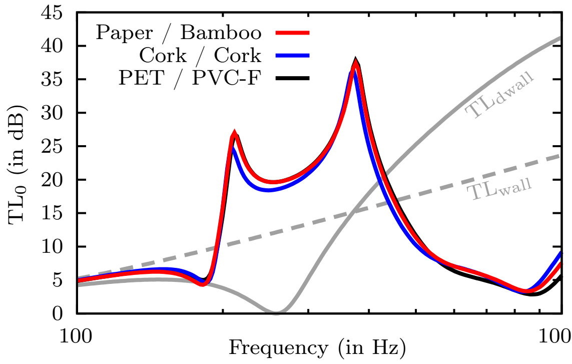

Figure 3: Normal incidence STL of the optimized PAM panel designs.

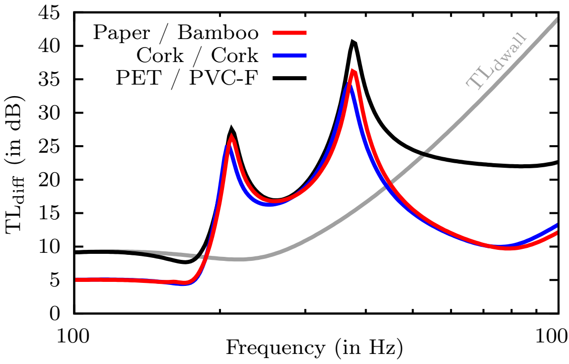

Figure 4: Diffuse incidence STL of the optimized PAM panel designs with porous material layers.

acoustic performance is also nearly optimal under diffuse incidence with porous materials added. At frequencies above 400 Hz, however, the STL of the PAM panel consisting of PET/PVF-F and rock wool clearly surpasses that of the other two variants using hemp, even though the hemp layer is thicker than the of rock wool layer. The main reason for this is that the flow resistivity of rock wool is over ten times higher than that of hemp (see Table 3). Since the flow resistivity is a key parameter for sound absorption, especially in the higher frequency range, the STL of the PAM panel with rock wool is much higher above 400 Hz. Other sustainable porous materials have actually been shown to have a similar flow resistivity as rock wool. For example, Yang and Li [12] showed that ramie fibres can have a flow resistivity of over $120\,\mathrm{kN\,s/m^4}$, which is close to the value for rock wool. However, with a density of $440\,\mathrm{kg/m^3}$, a ramie fibre layer will need to be considerably thinner than the rock wool layer, which will also affect the sound absorption. The effect of ramie fibre layers in the optimized PAM panels could not be studied here, because not all material parameters that are required in the Johnson-Champoux-Allard model were available in the literature for this material.

Conclusions

In the present work, a numerical study of the sound insulation characteristics of acoustic metamaterial panels made of sustainable materials was presented. The panels consisted of two PAM layers with strip masses, separated by an 100 mm thick air gap partially filled with porous material. PAM panels made of cork only as well as paper/bamboo were designed using optimizations and compared to an optimized PAM panel design made of mineral oil based materials (PET/PVC-F). For the porous material, hemp was used in both sustainable PAM panel designs, whereas rock wool was chosen for the PET/PVC-F design. A comparison of all three PAM panel designs showed that the acoustic performance within the frequency band targeted in the optimizations (200 Hz to 400 Hz) is not affected by the material selection under both normal and diffuse incidence excitation. This indicates that sustainable materials are a viable option for designing noise control solutions that have a reduced impact on the environment. The main difference in the results presented here was found at higher frequencies, where the substantially higher flow resistivity of rock wool led to higher absorption of sound waves compared to hemp. Therefore, optimizing the flow resistivity of porous materials made of sustainable materials could be a fruitful further research direction to further improve the performance of sustainable PAM panels.

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