1 Realisation of a thermoformed vibro-acoustic
2 metamaterial for increased STL in acoustic resonance
3 driven environments

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8 **Abstract**

9 This paper discusses the design and validation of a thermoformed locally
10 resonant metamaterial panel tuned to attenuate the excitation of the first
11 acoustic mode of a cavity. Moreover, it brings resonant metamaterials closer
12 to industrial realisations by exploiting a cheap and widely used production
13 process. The concept is explained, and it is shown how the stop band
14 can be tuned to a targeted frequency. Additionally, multiple stop bands
15 are achieved by combining two differently tuned locally resonant parts in
16 the same metamaterial panel. The proposed thermoformed metamaterial
17 panels have **similar weight as the original panel** and superior experimentally
18 evaluated insertion loss performance in the frequency range of the stop band.

19 *Keywords:* Locally resonant metamaterial, stop band, thermoforming,
20 acoustic mode suppression

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21 1. Introduction

22 Thermoformed panels are widely used in industry, they are for example
23 used in the cabin roof of agricultural machinery. In such a cabin, the first
24 acoustic mode can be the cause of noise annoyance for the driver, occurring
25 usually in the low frequency region (100 to 200 Hz), where classical solu-
26 tions based on mass addition and absorption material are highly inefficient.
27 Therefore, a novel resonant metamaterial solution [1, 2, 3, 4] is proposed to
28 attenuate this vibro-acoustic insulation problem.

29 Resonant metamaterials combine lightweight design and pronounced
30 noise and vibration attenuation performance in tunable and well-defined
31 frequency ranges, referred as stop bands. To create a resonant metamate-
32 rial, resonators are added to a host structure on a subwavelength scale. The
33 fano-type interference between the waves traveling in the host structure and
34 the waves induced by the resonators at their natural frequency create the
35 stop band effect, leading to a pronounced vibration attenuation and high
36 sound transmission loss (STL) [5, 6, 7].

37 This paper discusses the use of metamaterials to attenuate the excitation
38 of the first acoustic mode of a cavity. Instead of using expensive and time
39 consuming production methods as often applied to validate a design con-
40 cept [4, 8, 9], thermoforming is exploited to produce a cheap and practically
41 realizable metamaterial solution for industrial applications. The result is a
42 panel similar weight compared to the original panel and with strong noise
43 insulation performance in the frequency region of the tuned stop band. The
44 tunability of the thermoformed metamaterial panel is exploited and demon-
45 strated through experimentally acquired sound insertion loss (IL) results of
46 stop bands designed for different frequencies. A mixed configuration is also

47 studied, where two stop bands are created in one panel. Finally, represent-
48 ing the harvester cabin vibro-acoustic problem, the metamaterial is tuned
49 to the first acoustic mode of a cavity to show its potential to attenuate the
50 excitation of this mode due to external acoustic excitation.

51 2. Problem definition

52 A twin sheet thermoformed panel is chosen to apply the novel meta-
53 material solution, which is composed of a Acrylonitrile Butadiene Styrene
54 - Polymethyl Methacrylate (ABS-PMMA) thermoformed 2.78 mm thick
55 panel, visible in Figure 1, and an ABS flat 3.51 mm thick panel, not visible
56 in Figure 1, which are connected through ultrasonic welding. The ABS-
57 PMMA panel is thermoformed to create pillars to connect to the flat ABS
58 panel, such that when both are combined, a light but stiff panel is obtained.
59 This can also deteriorate the noise insulation performance.

Figure 1: Thermoformed panel chosen to apply the metamaterial solution (left) and the metamaterial realization (right).

60 The material properties of each panel are retrieved through model up-
61 dating of the panels before thermoforming and are shown in Table 1 [10].

These material properties are used in a finite element (FE) model to identify the stop band frequency region, presented in Section 3.

Table 1: Material properties of the two panels obtained through model updating.

	Young's modulus	Poisson's ratio	Density	Structural damping
ABS-PMMA				
(thermoformed)	1600 MPa	0.4	971.35 kg/m ³	1.7%
ABS	1980 MPa	0.4	1025.1 kg/m ³	2.88%

3. Metamaterial design

The thermoformed panel is periodic and characterized by a 69×73 mm unit cell (UC), being in a sub-wavelength scale until 421 Hz [2], covering the targeted frequency band (Figure 2). Its inherent periodicity opens the path to use dispersion curves to predict the stop band of the metamaterial solution. The dispersion curves are obtained by combining FE based UC modelling with the Bloch-Floquet boundary conditions [11, 12, 13]. In this way, the free wave propagation in an infinite panel composed of infinitely repeated UCs is analysed. For undamped structures, stop bands can be identified as frequency ranges for which no free wave propagation is found in any direction. In order to speed up calculation time, only the wave propagation along the irreducible Brillouin contour (IBC) is studied, which is shown to be sufficient in most cases [11, 14].

The resonant metamaterial solution is created by milling a slit in the thermoformed panel (Fig. 1). This creates a local resonance mode in the system, leading to a stop band in the acoustically relevant bending waves at 182 – 185 Hz for the slit-geometry of configuration A (Fig. 3b). In the second design, the resonant part is tuned by adding a 2 mm thick PMMA

Figure 2: Bare UC (right), UC with resonant part made by slits (center) and two different tunings of the resonant part through mass addition (left).

82 piece at the tip of the resonant part covering it completely (Configuration
 83 B). This shifts the natural frequency of the resonant part, and consequently
 84 shifts the stop band frequency region to 135 – 142 Hz (Fig. 3c). This stop
 85 band is slightly wider than the one obtained for configuration A due to
 86 the mass addition [13]. In a practical realisation, the tuning can be done
 87 by changing the geometry of the resonant slit, and hence changing the
 88 resonance frequency of the local resonance mode. The two stop bands of
 89 configuration A and B are combined by mixing the two configurations UCs
 90 in a chequerboard manner (Configuration Mixed). The dispersion diagram
 91 for this configuration exhibits stop band behaviour at 134 – 138 Hz and at
 92 179 – 181 Hz (Fig. 4). These stop bands are narrower when compared to
 93 Configuration A and B, respectively, since only half of the locally resonances
 94 are tuned to the same natural frequency in a same area [6]. They also lie in
 95 slightly lower frequency due to interaction of the two different tuned locally
 96 resonant parts. Finally, to tune the stop band to the first mode of the cavity

97 a third configuration is studied where the PMMA piece covers 6 mm of the
 98 tip of the resonant part and weighs 0.5 g (Configuration C) (Fig. 2), leading
 99 to a stop band at 155 – 160 Hz.

Figure 3: Along the IBC (a) the dispersion curves of the metamaterial Configuration A (b) show a stop band for the bending waves, which when a PMMA piece is added on the resonant part to create Configuration B shifts to a lower frequency (c).

Figure 4: Along the IBC Fig. 3a, the mixed configuration UC (a) dispersion curves (b) show two stop bands close to the stop band frequency regions of Configuration A and B.

100 4. Test setup

101 Two measurements are performed, (i) IL to assess the metamaterial so-
102 lution insulation performance and (ii) sound pressure level (SPL) measure-
103 ments to assess the metamaterial potential to attenuate the excitation of
104 the first mode of the cavity.

105 4.1. *Insertion loss*

106 The IL of the thermoformed panels is evaluated using the KU Leuven
107 Soundbox [15]. The cavity has an A2 aperture size (420×594 mm), which
108 can be closed by a clamped panel. The sound power is measured using a
109 B&K sound intensity PP probe type 2681 with a spacer of 50 mm, which
110 allows measurements from 31.5 Hz to 1600 Hz [16].

The panels' IL is calculated as:

$$IL(f) = 10 \log_{10} \frac{W_{open}}{W_{closed}} \quad (1)$$

111 where W_{open} and W_{closed} are the measured sound power through the A2
112 aperture without and with tested panel installed respectively and when
113 excited by a loudspeaker inside the Soundbox.

114 4.2. *Sound pressure level measurements*

The KU Leuven Soundbox has its first acoustic mode at 156 Hz [15].
Therefore, to assess the effectiveness of the metamaterial panel to attenuate
the excitation of this mode due to an external noise source, the metamaterial
panel configuration C is clamped on the Soundbox and excited using an
external loudspeaker 450 mm distant from the panel. The SPL inside the

Soundbox is measured by two PCB microphones type 378B20 (Figure 5).

An RMS value is calculated as:

$$SPL_{RMS} = \sqrt{\frac{1}{2}(SPL_{Mic1}^2 + SPL_{Mic2}^2)} \quad (2)$$

where SPL_{Mic1} and SPL_{Mic2} are the SPL measured by microphones 1 and 2.

Figure 5: Experimental test setup.

5. Results

5.1. Insertion Loss

The stop band effect can be noticed for the three metamaterial cases, represented by a pronounced improvement in IL (Fig. 6). On the one hand, around the stop band lower bound a peak in IL is perceived, and the metamaterial cases surpass the IL performance of the original panel. On the

Figure 6: IL for three configurations: A, B and Mixed. The peak in IL shows good agreement with the predicted stop band for the configuration B (solid black lines) and A (dashed black lines).

other hand, a dip in IL is also noticed around the stop band upper bound where the metamaterial cases IL are surpassed by the IL of the original panel. This can be explained by the dynamic mass behaviour of resonant metamaterials. Due to the in phase motion of the host structure and resonator, the dynamic mass increases before the lower bound of the stop band, where its maximum is reached, causing an improvement in the IL before this frequency region and the peak in IL. After resonance, the resonator and the host structure move out of phase, and the dynamic mass reduces. The latter happens until the upper bound of the stop band, where its minimum is reached, causing the measured drop in the IL performance for the metamaterial cases [17, 18]. For all cases, this behaviour can be noticed around the predicted stop band regions. Slight variation of the location of the peaks and dips with respect to the predicted stop band are expected to be caused due to variations of the resonance frequencies of the different locally resonant parts because of variability during production. This vari-

ability is also the reason why the measured stop band is a marginally wider than predicted [13]. Moreover, the described behaviour is less pronounced for the mixed configuration since only half of the locally resonant parts are tuned to a same resonance frequency. [6].

5.2. Acoustic mode excitation attenuation

Figure 7: RMS of the **frequency response function** (FRF) of the pressure measured as described in the Section 4 for the bare panel and the metamaterial panel on the configuration C. The two black vertical lines represent the predicted stop band for the configuration C. The dB reference used is 2×10^{-5} Pa.

For the original panel, a peak in the sound pressure level at 156 Hz can be clearly noticed due to the first acoustic mode of the cavity (Fig. 7). However, for the metamaterial panel in the configuration C, this peak is strongly attenuated due to the stop band effect which increases the impedance of this panel, reaching 8 dB of attenuation peak-to-peak. After the stop band, the acoustic behavior of the panel is worsened in comparison to the original panel, as already discussed in a earlier work [19]. However, one can argue that for the metamaterial configuration C the acoustic response of the cavity

151 is more evenly distributed than in the bare configuration. The effect can be
152 seen and heard via the following link:<https://www.youtube.com/watch?v=GWHaiEnx4ks>.

153 **6. Conclusion**

154 This paper shows the potential of a vibro-acoustic metamaterial realised
155 by thermoforming, an already largely used and cost efficient manufacturing
156 process. This brings the metamaterial solution close to a practical applica-
157 tion avoiding the use of expensive non-common industry manufacturing pro-
158 cesses. The metamaterial effect can be easily tuned and combined, obtaining
159 an enhancement in the experimentally obtained IL in targeted stop band
160 frequencies. Moreover, the acoustic insulation potential of this metamate-
161 rial solution in an acoustic resonance driven environment is demonstrated.
162 The solution is lighter than the original panel, has the same volume, and
163 achieves a 8 dB peak-to-peak reduction in the sound pressure level of the
164 first acoustic mode inside the cavity.

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References

- [1] P. Sheng, X. Zhang, Z. Liu, C. Chan, Locally resonant sonic materials, *Physica B: Condensed Matter* 338 (1) (2003) 201–205 (2003).
- [2] P. F. Pai, Metamaterial-based broadband elastic wave absorber, *Journal of Intelligent Material Systems and Structures* 21 (5) (2010) 517–528 (2010).
- [3] A. Hall, E. Calius, G. Dodd, K. Chan, Development of locally resonant structures for sonic barriers, in: *Health Monitoring of Structural and Biological Systems 2013*, Vol. 8695, International Society for Optics and Photonics, 2013, p. 86953M (2013).
- [4] C. Claeys, E. Deckers, B. Pluymers, W. Desmet, A lightweight vibro-acoustic metamaterial demonstrator: Numerical and experimental investigation, *Mechanical Systems and Signal Processing* 70 (2016) 853–880 (2016).
- [5] C. Goffaux, J. Sánchez-Dehesa, A. Yeyati, P. Lambin, A. Khelif, J. Vasseur, B. Djafari-Rouhani, Evidence of fano-like interference phenomena in locally resonant materials, *Physical Review Letters* 88 (22) (May 2002). doi:10.1103/physrevlett.88.225502.
URL <http://dx.doi.org/10.1103/PhysRevLett.88.225502>
- [6] C. Claeys, N. G. R. de Melo Filho, L. Van Belle, E. Deckers, W. Desmet, Design and validation of metamaterials for multiple structural stop bands in waveguides, *Extreme Mechanics Letters* 12 (2017) 7–22 (2017).
- [7] Y. Xiao, J. Wen, X. Wen, Sound transmission loss of metamaterial-based thin plates with multiple subwavelength arrays of attached resonators, *Journal of Sound and Vibration* 331 (25) (2012) 5408–5423 (2012).
- [8] T. Yu, G. A. Lesieutre, Damping of sandwich panels via three-dimensional manufactured multimode metamaterial core, *AIAA Journal* (2017).
- [9] R. Zhu, X. Liu, G. Hu, C. Sun, G. Huang, A chiral elastic metamaterial beam for broadband vibration suppression, *Journal of Sound and Vibration* 333 (10) (2014) 2759–2773 (2014).
- [10] W. Heylen, S. Lemmens, P. Sas, *Modal analysis theory and testing*, KU Leuven, PMA division, 2014 (2014).
- [11] L. Brillouin, *Wave propagation in periodic structures*, 2nd Edition, McGraw-Hill Book Company, 1946 (1946).

- 203 [12] P. A. Deymier, Acoustic metamaterials and phononic crystals, Vol. 173, Springer
204 Science & Business Media, 2013 (2013).
- 205 [13] C. Claeys, K. Vergote, P. Sas, W. Desmet, On the potential of tuned resonators to
206 obtain low-frequency vibrational stop bands in periodic panels, Journal of Sound
207 and Vibration 332 (6) (2013) 1418–1436 (2013).
- 208 [14] F. Maurin, C. Claeys, E. Deckers, W. Desmet, Probability that a band-gap ex-
209 tremum is located on the irreducible brillouin-zone contour for the 17 different plane
210 crystallographic lattices, International Journal of Solids and Structures 135 (2018)
211 26–36 (2018).
- 212 [15] M. Vivolo, Vibro-acoustic characterization of lightweight panels by using a small
213 cabin, Ph.D. thesis, PhD Thesis, Arenberg Doctoral School, University of Leuven
214 (2013).
- 215 [16] B. . Kjaer, Sound Intensity (br0476), DK-2850 Naerum, Denmark (Revision Spetem-
216 ber 1993).
217 URL <https://www.bksv.com/doc/br0476.pdf>
- 218 [17] N. de Melo Filho, L. Van Belle, C. Claeys, E. Deckers, W. Desmet, Dynamic mass
219 based sound transmission loss prediction of vibro-acoustic metamaterial double pan-
220 els applied to the mass-air-mass resonance, Journal of Sound and Vibration 442
221 (2019) 28–44 (2019).
- 222 [18] C. Sugino, Y. Xia, S. Leadenham, M. Ruzzene, A. Erturk, A general theory for
223 bandgap estimation in locally resonant metastructures, Journal of Sound and Vi-
224 bration 406 (2017) 104–123 (2017).
- 225 [19] C. Claeys, P. Sas, W. Desmet, On the acoustic radiation efficiency of local resonance
226 based stop band materials, Journal of Sound and Vibration 333 (14) (2014) 3203–
227 3213 (2014).