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Tunability of stop bands in thermoformed vibro-acoustic metamaterials solutions for increased noise insulation

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ABSTRACT

Recently, resonant metamaterials have caught attention due to their lightweight design and superior noise insulation performance at defined and tunable frequency ranges, called stop bands. Nevertheless, the production processes of such noise insulation solutions are still expensive and therefor hindering application in industry. This paper explores the use of thermoforming, which is a cheap and common industrial production process, to manufacture a metamaterial panel. In this way, resonant metamaterials are brought closer to a realizable industrial noise insulation solution. In previous work, the authors have shown the use of such a thermoformed metamaterial panel in a resonance driven acoustic environment. In this paper, the main focus is on the tunability and robustness of the concept. The structural vibration behaviour and the noise insulation performance of the produced metamaterial panels are experimentally assessed by hammer testing and insertion loss measurements respectively. A strategy to widen the zone of influence, by combination of stop bands, is also experimentally investigated by combining two different tuned locally resonant parts in one panel. Furthermore, a panel with less resonant parts is manufactured to verify the robustness of the proposed solution. In conclusion, the created metamaterial thermoformed panel is lighter and provides superior experimentally evaluated noise and vibration insulation performance for all the studied cases in the frequency regions of their tuned stop bands.

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1. INTRODUCTION

In recent decades, more strict regulations on carbon dioxide emissions have led to lightweight designs [1]. At the same time, customer demands for noise and vibration harshness (NVH) comfort have also increased. Nevertheless, lightweight structures offer a poor NVH performance due to their low mass and high stiffness. Furthermore, classical NVH solutions are mainly based on mass or volume addition and do not align with the lightweight requirements. Consequently, novel NVH solutions are sought, and resonant metamaterials come to the fore as a potential solution [2].

Resonant metamaterials offer the potential to combine lightweight design and remarkable NVH performance in well-defined frequency ranges called stop bands. Stop bands are frequency regions where free wave propagation is prohibited. They are created due to a Fano-type interference induced by resonant structures when added to a host structure in a subwavelength scale [3]. In these frequency regions, a high noise and vibration insulation performance is expected [4, 5]. The production processes commonly used to manufacture these metamaterial structures, e.g. additive manufacturing, are still uncommon to industry and come with commercially non-viable costs [6, 7].

In this paper, the metamaterial solution is manufactured using thermoforming, a common and cheap industrial production process. The structural vibration behaviour and noise insulation performance of the thermoformed metamaterial structures are experimentally assessed through hammer testing and sound insertion loss (IL) measurements, respectively. The tunability of the solution is demonstrated as well as the combination of stop bands in a single panel. The former shows the versatility of the solution and the latter a possible manner to widen the stop band effect in frequency. The robustness of the proposed solution is also studied by reducing the number of resonant structures in one panel.

The paper is outlined as follows. After the introduction, the thermoformed panel used to apply the metamaterial solution is described. Later, the metamaterial solution is designed and tuned and the different configurations are explained. Then, the test setup used to evaluate the NVH performance of the metamaterial thermoformed panels is described, and their experimental results are discussed. The paper ends with the main conclusions.

2. THERMOFORMED PANELS

Thermoformed panels are among several applications applied in agricultural machinery where they compose the cabin roof. In these cabins, the first acoustic mode poses a NVH problem. This mode generally occurs in the 100 – 200 Hz frequency range. In this low frequency range, classical NVH solutions fail. However, metamaterials can be a possible solution to avoid excitation of this mode, when their stop band is tuned at these frequency range [8].

In this paper, the thermoformed panel used to apply the metamaterial solution is composed of Acrylonitrile Butadiene Styrene-Polymethyl Methacrylate (ABS-PMMA) 2.78 mm thick thermoformed panel, and an ABS 3.51 mm thick flat panel, which are connected through ultrasonic welding (Figure 1). The material properties of the panels are obtained through model updating of the separate flat panels before thermoforming (Table 1) [8]. Due to the test rig available for the experimental tests, explained later in the paper, the thermoformed panels have dimensions of 640 x 840 mm, although, only an A2 (420 x 594 mm) area is tested.

Table 1: Material properties of the twins sheet thermoformed panels [8].

	$\rho (kg/m^3)$	$E\ (MPa)$	υ	Struct. Damping (%)	Thickness (mm)
ABS-PMMA (thermoformed)	971.35	1600	0.4	1.7	3.51
ABS	1025.10	1980	0.4	2.88	4.23

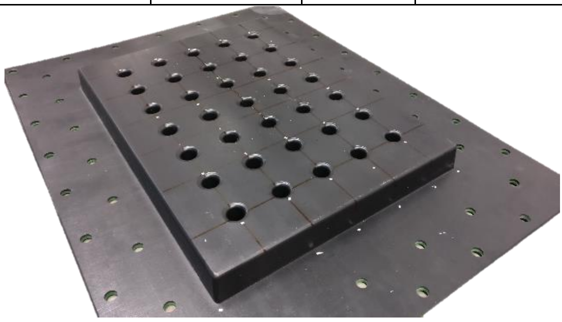


Figure 1: Thermoformed twin sheet panel used to apply the metamaterial solution. The ABS-PMMA thermoformed panel is visible.

3. METAMATERIAL SOLUTION

The selected thermoformed panel is periodic and has a unit cell (UC) of 69x73 mm (Figure 2). This UC is in a subwavelength scale until 421 Hz, which is well above the target frequency for the resonant structures to induce the Fano-type interference and create a stop band.

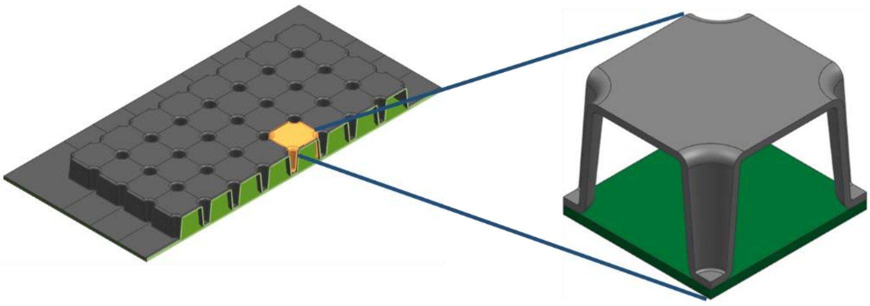


Figure 2: The UC is defined as the smallest periodic part of the structure.

The resonant structure is created by milling a slit in the thermoformed ABS-PMMA panel (Figure 3). The created metamaterial thermoformed panel (Configuration A) is 3.7 % lighter than the original panel, and no new manufacturing process is added since milling is already commonly used when producing thermoformed parts. Furthermore, to explore tunability, a second configuration, configuration B, is created by adding a PMMA piece 2 mm thick at the end point mass of the resonant slit using double sided tape. This makes the panel 2.6 % heavier than the original. In a product application, this tuning can be done by re-designing the slit.

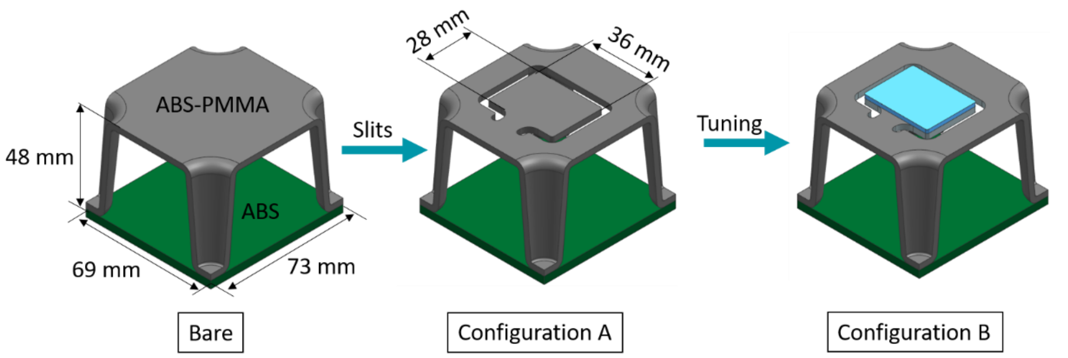
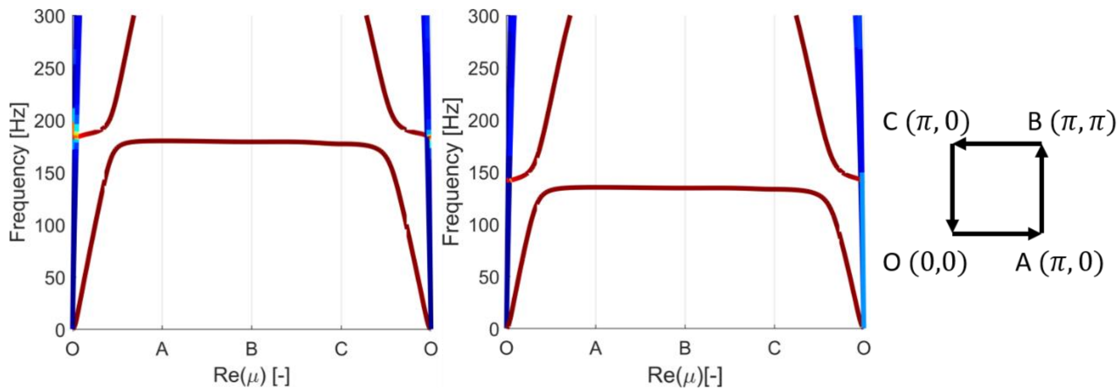


Figure 3: The resonant structure, which is created by milling a slit in the thermoformed panel, is tuned to a different frequency by adding a 2 mm thick PMMA piece on the end point mass of it.

The slits are designed to tune the stop bands to the targeted frequency range. For this purpose, the stop bands are predicted using dispersion curves obtained through finite element (FE) based UC modelling [2, 3]. Considering an undamped structure, the stop bands are frequency wave gaps in the calculated dispersion curves, which are calculated along the irreducible Brillouin contour shown in Figure 4 [9]. The stop bands are created in the acoustically relevant bending waves from 181 Hz to 187 Hz for configuration A, and from 137 Hz to 147 Hz for configuration B. The configuration B stop band is predicted to be wider than the configuration A stop band due to the mass addition [2].



(a) (b) (c)

Figure 4: The dispersion curves for the Configuration A (a) and Configuration B (b) are calculated along the irreducible Brillouin contour (c). The red lines represents the acoustically relevant bending waves where a stop band can be noticed in both dispersion curves.

A mixed configuration is created by combining the configurations A and B in one panel in a checkboard fashion, which has the same weight of the original panel (Figure 5). Consequently, two stop bands are predicted in the calculated dispersion curves (Figure 6): 134 – 138 Hz and 179 – 181 Hz, which corresponds to the predicted stop bands for configurations B and A respectively. The stop bands for the mixed configuration are narrower compared to the pure cases since only half of the resonant slits tuned to the same frequency are present in a same area [5].

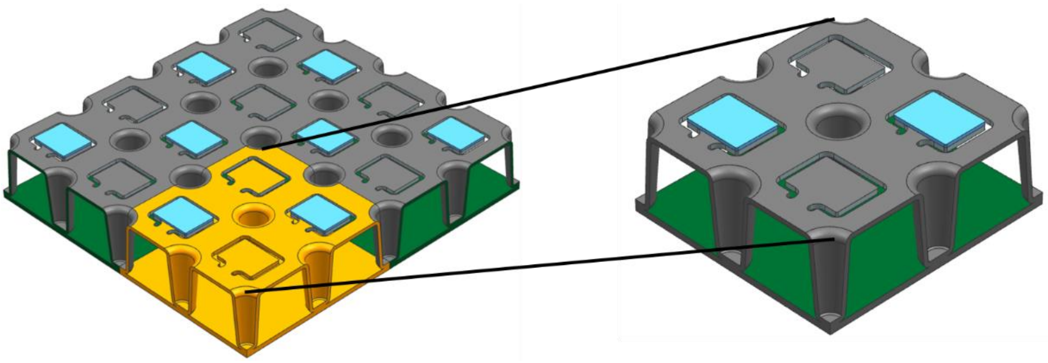


Figure 5: Representation of the mixed configuration created by combining the configurations A and B (left) and its UC (right).

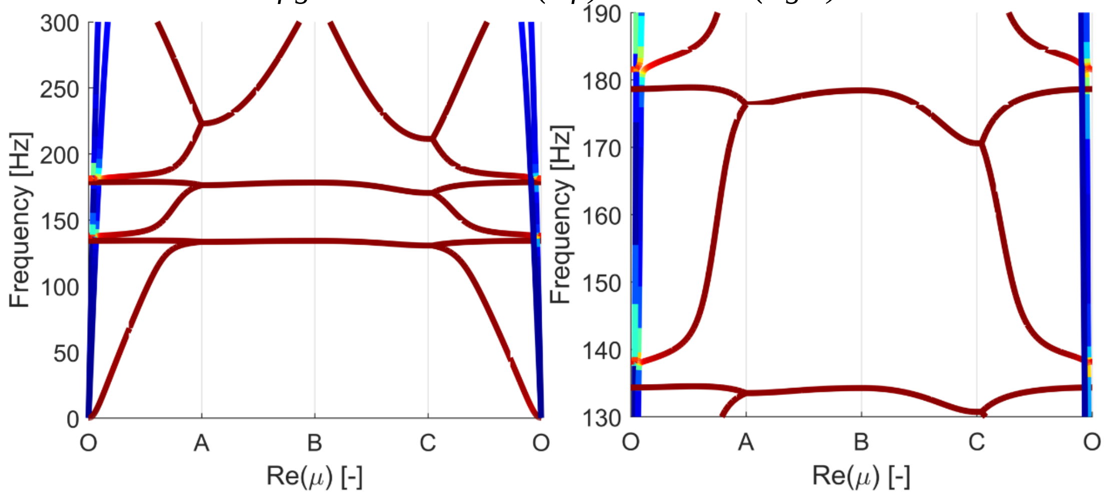


Figure 6: Dispersion diagram obtained for the mixed configuration UC (left) calculated over the defined Brillouin contour in Figure 4(c). The red lines represents the acoustically relevant bending waves where two stop bands can be noticed in the zoom of the dispersion curve (right).

Finally, also a thermoformed metamaterial panel in which for 12 unit cells no slits are made (Configuration C) is evaluated. The realised thermoformed metamaterial panels have the same dimensions as the original panel and configurations A and C are shown in Figure 7.

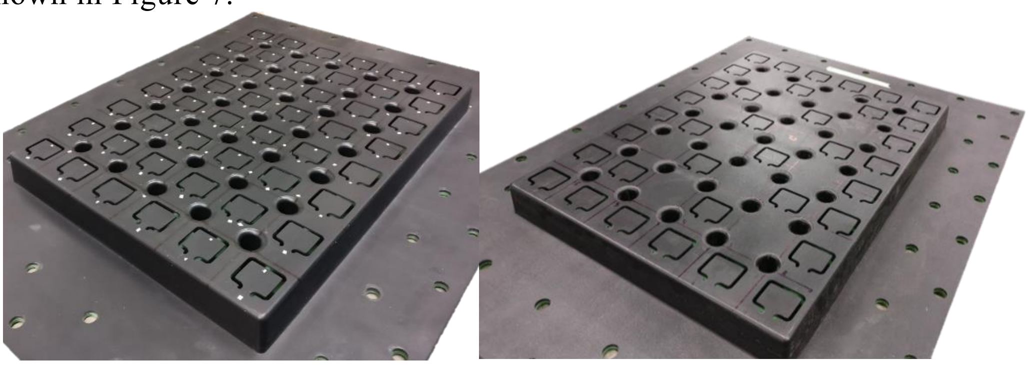


Figure 7: Thermoformed metamaterial panel: configuration A (left) and less resonant slits (right).

3. TEST SETUP

The structural vibrational behaviour and the noise insulation of the thermoformed panels are assessed with the panels clamped to the KU Leuven Soundbox [10] (Figure 8). The KU Leuven Soundbox is a cavity made of reinforced concrete with interchangeable front walls made of 35 mm thick aluminium where different panel sizes can be clamped. In this paper, the front wall with an A2 aperture is used, 52 bolts clamp the panel with a torque of 30 Nm applied on each.

Figure 8: The sound power of the KU Leuven Soundbox aperture open (left) and closed by the tested panel (right) when a loudspeaker (blue circle) excites the cavity is measured to calculate the IL of the tested panel [10].

The structural vibration behaviour is evaluated by impact testing on the non-thermoformed ABS panel. Due to reciprocity, 56 acceleration points are measured in a rectangular grid of 7x8 points while excited in the point shown in Figure 9. The impact hammer used has an impedance head type PCB 086C03 and a single lightweight accelerometer type PCB 35A24, weighing 0.8 g, is used.

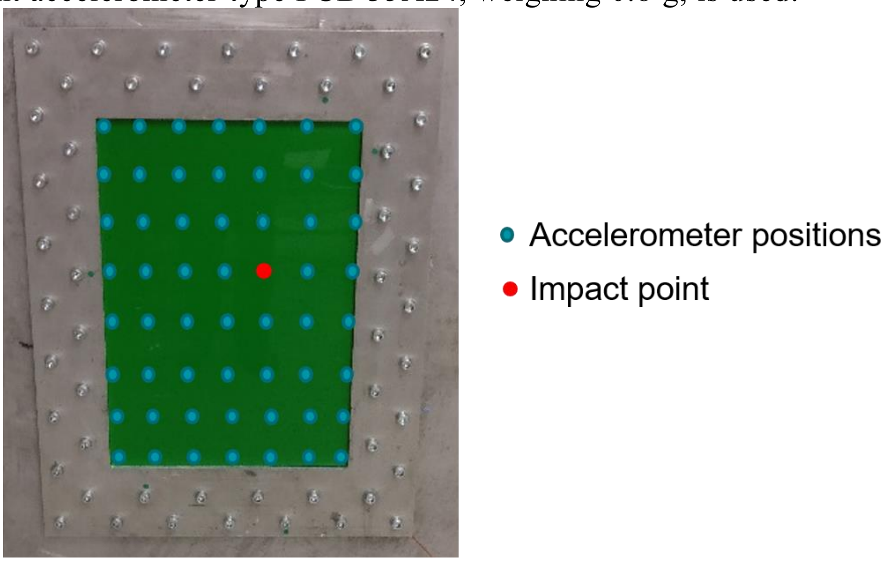


Figure 9: The structural vibration behaviour of the thermoformed panels is assessed by impact testing over a regular gird of 56 points.

The IL is calculated as:

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

where W_{open} and W_{closed} are the measured sound power radiated through the cavity A2 aperture open and closed by the tested panel respectively, excited by a loudspeaker. The sound power is measured using a B&K PP probe type 2681 with a spacer of 50 mm. The temperature during the measurements was 20ºC.

4. EXPERIMENTAL RESULTS

4.1 Structural vibration behaviour

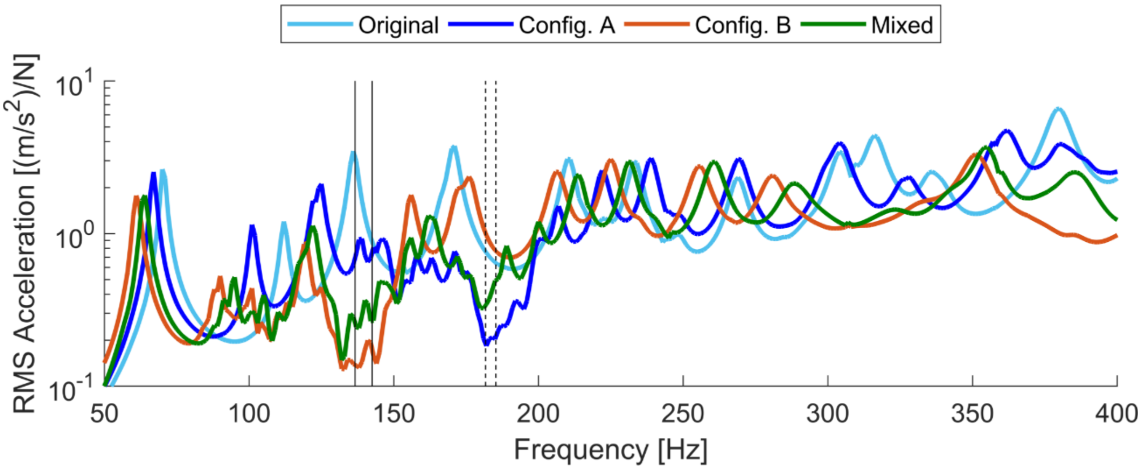


Figure 10: The calculated RMS acceleration over the 56 measurement points for the 4 cases studied: original, configurations A, B and mixed. The solid black vertical lines represent the predicted stop band for configuration B, and the dashed black vertical lines represent the predicted stop band for the configuration A.

The RMS acceleration of configuration A and B shows a pronounced vibration attenuation in the frequency region of their respective predicted stop bands (Figure 10). In addition, the mixed configuration presents two zones of vibration attenuation in the two predicted stop bands frequency regions. Nevertheless, the measured vibration attenuations due to the stop band effects are less wide and pronounced than for the configurations A and B. This happens since the tuning of only half of the resonant slits are to the same frequency in this configuration [5].

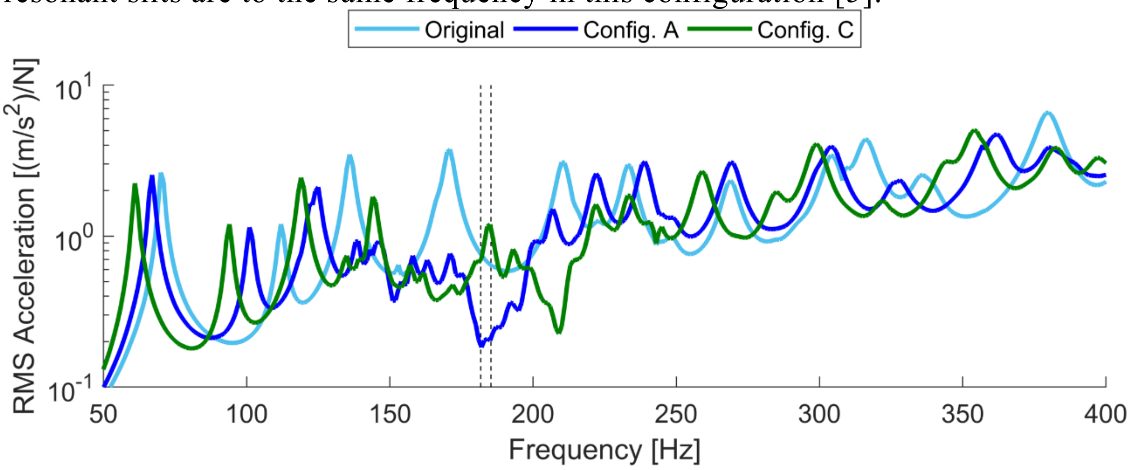


Figure 11: RMS acceleration calculated over the 56 measurement points for two cases: configurations A and C. The dashed black vertical lines represent the predicted stop band for the configuration A.

For the configuration C, the removal of the resonant slits causes the stop band effect to be less pronounced; however, the effect is still noticeable, albeit, shifted to a slightly higher frequency region (Figure 11). This shift to a higher frequency region can be due to manufacturing errors during the thermoforming process.

4.2 Noise insulation performance

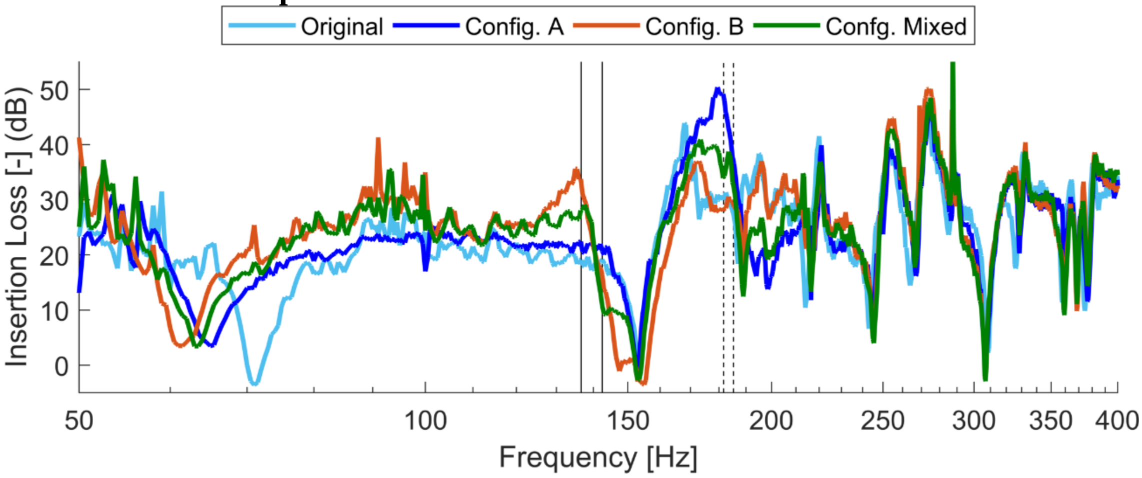


Figure 12: IL of 4 cases in study: original, configurations A, B and mixed. The solid black vertical lines represent the predicted stop band for configuration B, and the dashed black vertical lines represent the predicted stop band for the configuration A.

The measured ILs present a spiky behaviour due to the low frequency range analysed (Figure 12). Consequently, the structural behaviour of the panels is dominated by modal behaviour as can be seen by the measured dips in IL in the frequency region from 60 Hz to 70 Hz, which correspond to the first panel modes of each configuration. In addition, the influence of the modes of the acoustic cavity is also measured as can be seen by the measured dip in IL at 156 Hz, which is the first mode of the closed cavity [10].

The stop band effect can be clearly noticed in all metamaterial cases when compared to the original case. Around the lower frequency bound of the predicted stop bands, the IL of the metamaterial panels surpass the IL of the original panel, and around the higher frequency bound of the stop bands, the opposite can be noticed. This can be explained by the variation of dynamic mass of the metamaterial panels, which is maximum at the lower bound of the stop band and minimum at its higher bound [11].

For configurations A and B, the described behaviour is only noticed in the frequency region of the corresponding stop bands, and for the mixed configuration, in both stop bands frequency ranges due to the dual stop band behaviour present in this panel. However, this behaviour is less pronounced for the mixed configuration for the same reasons explained before. Therefore, it can be concluded that the proposed metamaterial can increase the IL of the panels without adding mass at a limited frequency range due to the stop band effect and that the region can be tuned by changing the resonance frequency of the resonator slit.

Figure 13 shows the IL results for the configuration C, the stop band effect is again less pronounced. Moreover, the peak attenuation happens in a slightly higher frequency as compared to the configuration A for the same reason explained in the previous section.

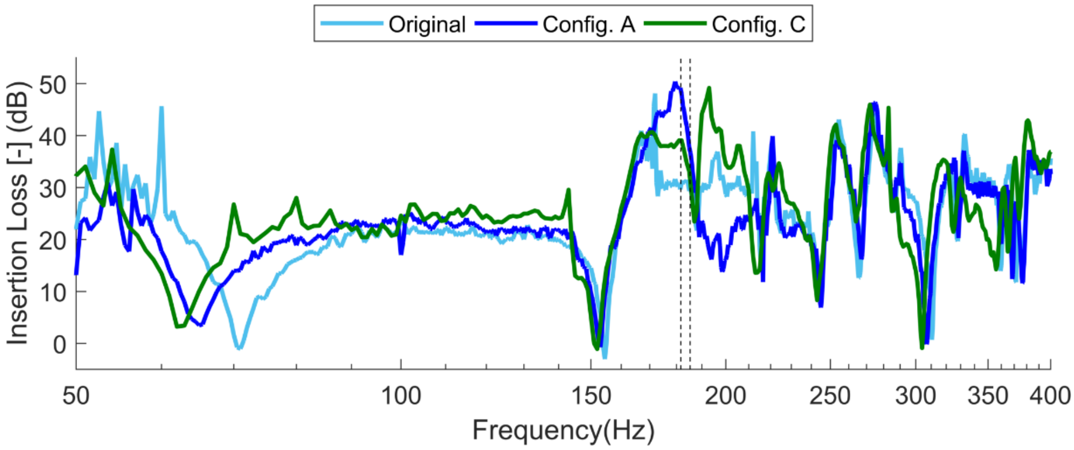


Figure 13: IL of 3 cases in study: original, configurations A and C. The dashed black vertical lines represent the predicted stop band for the configuration A.

5. CONCLUSION

This paper discusses the use of thermoforming to manufacture a metamaterial panel, which is lighter and has superior noise insulation performance than the original panel at the frequency region of the tuned stop band. This example brings metamaterials as a novel NVH solution closer to industrial reality, due to the potential to be manufactured by a cheap and commonly used production process. The tunability and combination of stop bands is also explored. The former shows the potential of the solution to be adapted for different frequency targets, and the latter shows that it is possible to widen its effect or target two different frequency regions in one metamaterial solution. The robustness of the solution to cases where less resonant slits would be present is also verified, and it is shown that the stop band effect still can be perceived structurally and acoustically, albeit less pronounced. Therefore, the metamaterial solution potential is demonstrated and brought closer to an industrial application. To hear and see the stop band effect in such thermoformed panel follow the link: https://www.youtube.com/watch?v=GWHeiEnx4ks.

6. ACKNOWLEDGEMENTS

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6. REFERENCES

1. Mallick, Pankaj K., ed. *Materials, design and manufacturing for lightweight vehicles*. Elsevier, 2010.
2. Claeys, C., Vergote, K., Sas, P., & Desmet, W. (2013). *On the potential of tuned resonators to obtain low-frequency vibrational stop bands in periodic panels*. Journal of Sound and Vibration, 332(6), 1418--1436. doi:10.1016/j.jsv.2012.09.047
3. C. Goffaux, J. Sanchez-Dehesa, A.L. Yeyati, P. Lambin, A. Khelif, Jo Vasseur, and B. Djafari-Rouhani. *Evidence of fano-like interference phenomena in locally resonant materials*. Physical Review Letters, 88(22):225502, 2002.

4. 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, Vol. 331, No. 25, (2012), pp. 5408–5423.
5. 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, Vol. 12, (2017), pp. 7–22.
6. T. Yu, G. A. Lesieutre, Damping of sandwich panels via three-dimensional manufactured multimode metamaterial core, AIAA Journal.
7. 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.
8. N. G. R. de Melo Filho, L. Sangiuliano, C. Claeys, E. Deckers and W. Desmet, *Vibro-acoustic metamaterial for increased STL in acoustic resonance driven environments*, Noise and vibration emerging methods – NOVEM 2018, Ibiza, Spain.
9. F. Maurin, C. Claeys, E. Deckers, W. Desmet, *Probability that a band-gap extremum is located on the irreducible brillouin-zone contour for the 17 different plane crystallographic lattices*, International Journal of Solids and Structures 135 (2018) 26{36.
10. M. Vivolo. *Vibro-acoustic characterization of lightweight panels by using a small cabin.* Diss. PhD Thesis, Arenberg Doctoral School, University of Leuven, 2013.
11. N. G. R. de Melo Filho, L. Van Belle, C. Claeys, E. Deckers, and W. Desmet, (2019). *Dynamic mass based sound transmission loss prediction of vibro-acoustic metamaterial double panels applied to the mass-air-mass resonance*. Journal of Sound and Vibration, 442, 28-44.