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# Locally resonant vibro-acoustic metamaterials as NVH solution applied to automotive applications

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## ABSTRACT

Lightweight materials and designs have been largely used in a variety of engineered structures due to the increasingly stringent ecological as well as economical requirements. Nonetheless, lightweight structures often combine low mass with high stiffness, which in turn leads to a reduced Noise, Vibration and Harshness (NVH) insulation performance. Classical solutions to enhance the vibro-acoustic performance of systems typically rely on the addition of mass or volume, which conflicts with the current lightweight design trends. In the search for novel solutions for noise and vibration reduction, locally resonant vibro-acoustic metamaterials have recently emerged and shown potential to tackle the challenges of not only achieving a good NVH insulation performance but also ensuring a lightweight and compact design. These engineered materials are formed by a sub-wavelength assembly of resonators onto a host structure. Their interaction results in tunable frequency ranges, known as stop bands, which are frequency zones where free wave propagation is not allowed. In these regions, a superior noise and vibration performance can be achieved, also in the hard-to-address low frequency range. This paper presents the potential of three locally resonant metamaterial solutions for noise and vibration mitigation applied to industrially relevant problems, where different production processes and materials are used.

**Keywords:** NVH, metamaterials, stop bands, industrially relevant problems

## 1. INTRODUCTION

In the past years, driven by economic and ecological aspects [1], lightweight materials and designs are gaining importance [2]. Nonetheless, due to their typically increased stiffness-to-mass ratio, this leads to a worse noise and vibration reduction performance, which diverges from customers' expectations as well as noise exposure regulations [3]. Classical countermeasures typically rely on adding volume and/or adding mass, which often leads to heavy and bulky NVH solutions, especially at the low frequency range, conflicting with the trends towards a lightweight design. Therefore, novel low mass and compact solutions are required to achieve a good NVH insulation performance while maintaining a lightweight design. Recently, metamaterials with locally resonant behavior have attracted the attention and proven to hold potential by combining lightweight and compact design with a superior noise and vibration reduction performance in desired frequency regions, referred to as stop bands. These are tuned frequency zones where free wave propagation is inhibited and can be created by the addition of resonant elements to an elastic host structure on a subwavelength scale i.e. on a scale much smaller than the wavelength of the targeted structural waves [4],[5]. To predict stop band behavior in a metamaterial system, Unit Cell (UC) modelling is typically used. Such numerical method makes use of infinite periodic structure theory and the Bloch-Floquet theorem [12], which is a computationally cheap tool to describe the response of an infinite periodic metamaterial system in terms of a UC. Locally resonant metamaterials can be manufactured by using different materials, production processes and integration strategies [6], which make them promising candidates for a variety of engineering applications at an affordable cost. In this paper, the potential of locally resonant metamaterials is shown by discussing three metamaterial solutions for cabin noise insulation in automotive applications, realized with varying manufacturing processes : 1) structure-borne noise mitigation on shock towers [7], 2) structure-borne tyre noise mitigation [9] and 3) sound transmission through a lightweight thermoformed panel [6].

This paper is organized around the three aforementioned application cases as follows. First, structure-borne noise reduction of a vehicle's shock tower with 3D printed locally resonant metamaterial patches is discussed. Second, structural-borne tyre noise mitigation by milled rubber locally resonant metamaterials is presented. Next, sound transmission reduction with a lightweight locally resonant metamaterial thermoformed panel is studied. Lastly, the main conclusions of the paper are summarized.

## 2. STRUCTURE-BORNE NOISE REDUCTION IN A VEHICLE'S SHOCK TOWER WITH 3D PRINTED PATCHES

### 2.1 NVH challenge overview

Tyre/road interaction in tyres leads to the excitation of acoustic tyre resonances and the transmission of vibrational energy to the vehicle. Typically, this energy propagates from the tyre contact patch, flowing through the suspension and the top mounts, then spreading into the wheel arches and other larger body panels. This can result in structure-borne noise around 200 Hz, which can often be perceived as an annoying tonal noise in the passenger compartment. To mitigate this noise issue, tuned vibration absorber (TVA) solutions can be used on the shock towers of the vehicle. Nonetheless, given the low-frequency nature of the problem, the TVA design can become rather heavy and large. Thus, the potential of a lightweight 3D printed locally resonant metamaterial solution is investigated to replace the classical TVA solutions while retaining the NVH insulation performance in the passenger compartment [7].

### 2.2 Problem definition

The car under investigation is a sport utility vehicle, which contains a MacPherson rear suspension as well as 235/60 R18 tyres. Due to the type of suspension system and tyre type used in the vehicle, high vibrational energy is introduced inside the car's body in a frequency region around 190 Hz. To reduce this energy propagation, the vehicle is equipped with a TVA on each of the rear shock towers, as shown in Figure 1. These TVAs are tuned to 190 Hz and add 1.46 kg to each of the rear shock towers of the car. This in turn results in an attenuation of the vibrational energy that enters the vehicle's body through the rear suspension around the tuned frequency range, which consequently reduces the noise levels in the passenger compartment. The goal of the locally resonant metamaterial application in this study is to replace the currently implemented TVA solution with a locally resonant metamaterial consisting of 3D printed patches with resonant elements to reduce the added mass without impairing the NVH performance [7].

Figure 1: Illustration of the right rear shock tower of the vehicle with an installed TVA [7].

### 2.3 Locally resonant metamaterial solution

The locally resonant metamaterial solution is designed such that it can be added to the rear shock towers of the considered vehicle. In this system, the shock towers are on the main transfer paths of vibrational energy between the tyres and the vehicle's body. The frequency range of interest is around 190 Hz, as in the current implemented TVA solution. For this application, the locally resonant metamaterial solution is designed by means of UC modelling to create stop band within the frequency range 193-224 Hz The resonant addition used in the designed resonant metamaterial solution is illustrated in Figure 2. Such resonator design enables low-frequency in-plane as well as out-of-plane bending modes and are made of polyamide using selective laser sintering 3D printing [7]. However, in case of a large production volume, the proposed resonator design can also be manufactured with other production processes such as injection moulding and different materials [8]. The locally resonant metamaterial solution is added to the rear wheel arches and on the top mounts in the vehicle's trunk. For practical installation purposes, the locally resonant metamaterial is designed by means of eight patches that possess a similar shape as the geometry of the wheel arches and top mounts. In the designed patches, the resonators are connected by means of a grid of flexible beams with rectangular cross-section of 4x1 mm, which ensures a suitable attachment of the patches on the surface. The locally resonant metamaterial patches are attached to the vehicle surface by using Loctite® 406$^{TM}$ contact adhesive. The locally resonant metamaterial solution added to the two shock towers of the vehicle has a mass of 1.52kg in total, therefore, reducing the added mass with respect to the current implemented TVA solution by 48% [7].

Figure 2: Illustration of the resonant addition on a UC (left) realized resonator (center) and the resonant metamaterial patch installed to the right shock tower in the vehicle (right).

### 2.4 Results

The locally resonant metamaterial insulation performance is validated experimentally with on-road driving tests and compared with the performance of the current implemented TVA solution. The tests are carried out with the vehicle moving at a constant speed of 50±2.5 kph on a smooth asphalt surface profile. The interior noise is assessed by three microphones (PCB Model 378B02), which are fixed between the head restraints and the seat backrest at three different locations: (i) the driver's right ear (D), (ii) front passenger's left ear (FP) and (iii) rear right passenger left ear (RP). Figure 3 shows that an outspoken PSD SPL peak at 198 Hz is present, especially for the bare configuration, in which the current TVA solution is able to reduce the SPL around 3 dB(A) within the frequency range of 185 Hz to 210 Hz. Furthermore, the designed locally resonant metamaterial solution further enhances the peak attenuation at 198 Hz with around 4 dB(A) while maintaining a comparable SPL performance in the other frequency ranges with respect to the TVA solution. For a demonstration video about this application, the reader is kindly referred to the following link https://bit.ly/3eqiWId.

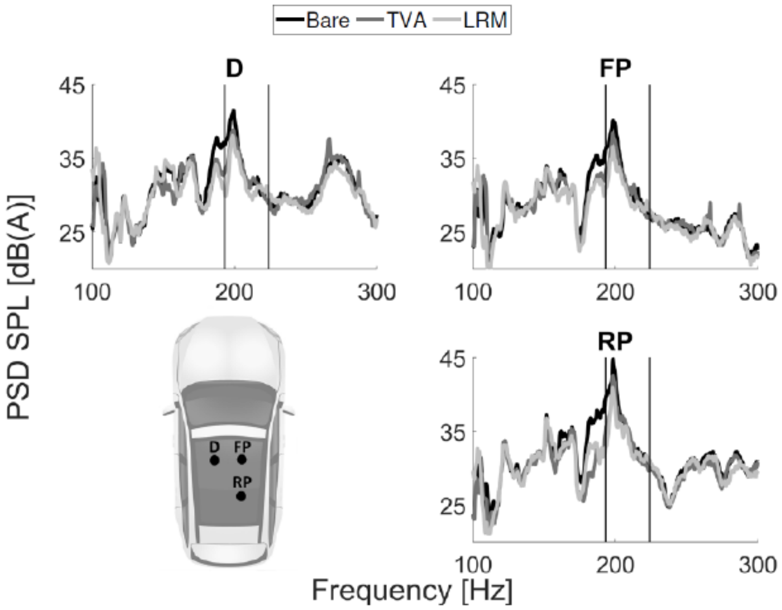

Figure 3: Comparison of PSD SPL for the tested configurations at three microphone locations. The vertical lines indicate the predicted stop band. The dB reference used is 2e-5 Pa [7].

## 3. REDUCTION OF STRUCTURE-BORNE TYRE/ROAD NOISE BY MILLED RUBBER RESONANT METAMATERIALS IN TYRES

### 3.1 NVH challenge overview

As indicated in the previous section, acoustic tyre resonances are typically excited by tyre-road interaction, which can lead to an annoying tonal noise in the vehicle's cabin around 200 Hz. As an alternative approach to mitigate this noise issue, discrete TVAs can be added on the tyre structure to target structural modes that can couple well with the tyre acoustic modes [10]. Nonetheless, such solution may not be practical given that the position of these TVAs relies on the vibration pattern of the targeted structural modes and the improvement can be achieved within a narrow frequency band. Thus, the potential of a locally resonant metamaterial solution is explored in this application, as such solution can work regardless of the vibration pattern given the subwavelength nature of the added resonant elements. This approach can lead to enhancement at and around the targeted acoustic modes due to the tunable-by-design stop band frequency range [9].

### 3.2 Problem definition

The tyre structures used in this application are commercially available tyres, type 205/55 R16, with a tread profile and steel rims 6.5x16 inch and are assembled on a "tyre-on-tyre" setup [11], as shown in Figure 4, in which the bottom tyre is to be treated with the locally resonant metamaterial concept. Each tyre weighs 9kg, and once assembled to the rim, inflated at 220kPa and balanced, the total weight of each wheel equals 17.5kg. The first acoustic tyre modes occur at 223Hz and 227Hz. The former is the horizontal acoustic mode while the latter is the vertical acoustic mode, which can lead to tonal noise in the passenger compartment.

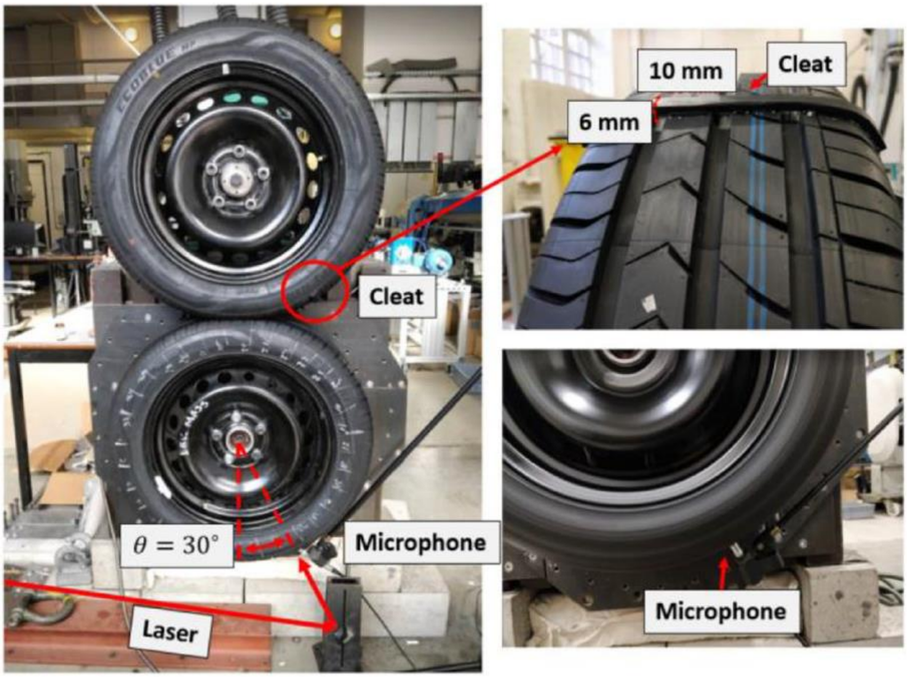

Figure 4: Illustration of the “tyre-on-tyre” setup for testing the tyre in rolling conditions [9].

### 3.3 Locally resonant metamaterial solution

The locally resonant metamaterial solution is designed to be added to the tyre in the aforementioned setup. The frequency region of interest lies around the frequency of the first acoustic modes of the tyre at 223Hz and 227Hz. In this application, the locally resonant metamaterial solution consists of introducing rubber resonant elements, as shown in the left-hand side of Figure 5, which are produced by using a computer numerical control milling machine. Such resonant design allows that in-plane and out-of-plane bending modes are targeted. In this case, the locally resonant metamaterial solution is designed to lead to a zone of attenuation within the 220-250 Hz frequency range, which is predicted by using UC modelling. In total, 144 rubber resonant elements are introduced to the tyre and glued by means of Loctite® 406$^{\mathrm{TM}}$ glue onto its inner liner. The total added mass is roughly 0.484kg, which leads to 5.37% of mass addition with respect to the bare tyre. For comparison purposes, an equivalent mass tyre is also produced, in which 144 rectangular pieces of rubber with same mass as the resonant elements are added with same distribution, as illustrated in the right-hand side of Figure 5.

Figure 5: Illustration of locally resonant metamaterial tyre (left) and equivalent mass tyre (right) configurations [9].

### 3.4 Results

The NVH insulation performance of the designed locally resonant metamaterial solution is experimentally verified by assessing the radial vibrations of the tyre and its near-field radiated SPL. The former are measured by means of a Polytec PSV-500 Scanning Laser Doppler Vibrometer in a point in the tread area located on a tread block at 32mm from the center of the cross section and at 150° in a clockwise direction from the center of the contact patch area, as shown in Figure 4, whereas the latter are measured by a microphone type PCB 378B02 that is placed 20mm radially away from the point where the vibrations in the tyre are measured. The tests are carried out for a rotation speed of the tyres of 10 rad/s, which roughly corresponds to a speed of 11.4 kph of a vehicle [9]. While rolling, the bottom tyre is excited by a rubber cleat that is attached to the upper tyre in order to simulate a road discontinuity. Three cases are analyzed: (i) the bare tyre, (ii) the equivalent mass tyre and (iii) the locally resonant metamaterial tyre. It can be seen in Figure 6 that a strong attenuation is achieved within the frequency range from 210 Hz to 280 Hz and that the trends of the radial vibration and the radiated SPL are in good agreement. Furthermore, the locally resonant metamaterial solution outperforms the equivalent mass case.

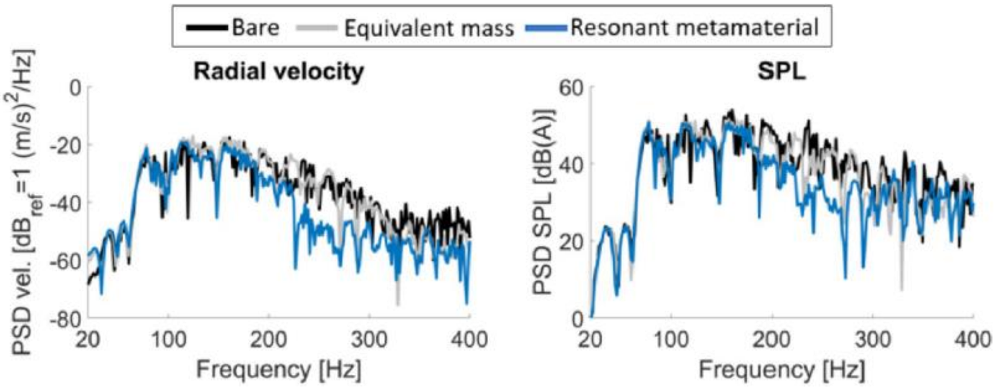

Figure 6: Comparison of PSD of the radial velocity (left) and SPL (right) for the bare, equivalent mass and locally resonant metamaterial tyre configurations [9].

## 4. SOUND TRANSMISSION IMPROVEMENT OF A LIGHTWEIGHT THERMOFORMED PANEL

### 4.1 NVH challenge overview

The engine noise in combine harvesters can propagate via their rooftop panel and excite the first acoustic mode of the cabin, which often occurs within the frequency range of 100-200Hz. Such mode can lead to noise annoyance for the harvester’s driver and, given the low-frequency nature of the NVH problem, classical countermeasures based on adding volume to increase sound absorption and/or adding mass to increase the sound transmission loss (STL) are typically highly inefficient. Taking inspiration of this application, an efficient locally resonant metamaterial solution is developed by using thermoforming for cost-efficient and fast production, and validated on an in-house setup [6].

### 4.2 Problem definition

The thermoformed panel constitutes an assembly of an A2 size twin-sheet Acrylonitrile Butadiene Styrene - Polymethyl Methacrylate (ABS-PMMA) panel, as depicted in the left-hand side of Figure 7. Its top sheet visible in the figure is 2.78 mm thick whereas its bottom sheet is 3.51 mm thick, in which the former has pillars that are ultrasonic-welded to the latter. Albeit the resulting thermoformed panel is lightweight, it possesses a poor noise insulation performance.

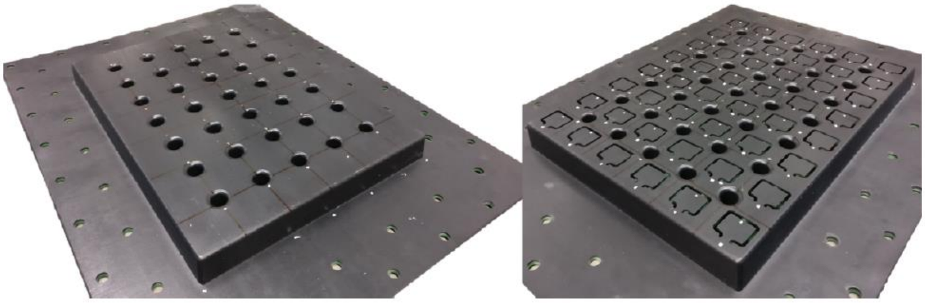

Figure 7: Bare (original) thermoformed panel (left) and locally resonant metamaterial realization (right) [6].

### 4.3 Locally resonant metamaterial solution

In this application, the locally resonant metamaterial solution consists of milling a slit in the top sheet of the panel, as illustrated in Figure 8. This process generates a resonant element that is integrated in the thermoformed panel as a cantilever beam like resonator that resonates at the desired/designed frequency. The resonant inclusion is further fine-tuned to 156 Hz by adding a 2mm thick and 6 mm wide mass of PMMA of 0.5 g to the tip of the resonant element, as shown in the right-hand side of Figure 8. This fine-tuning occurred such that the resonator design enables the creation of stop band behavior from 155-160 Hz, which corresponds to the frequency region of the first acoustic mode of the acoustic cabin used for validation. Here, the stop band limits are also predicted by applying UC modelling.

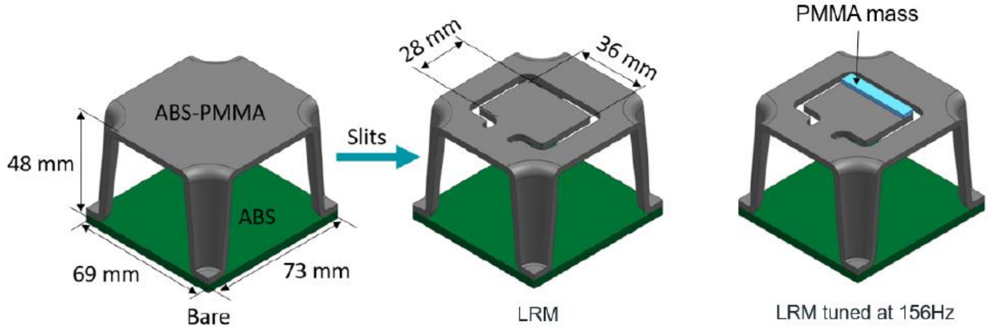

Figure 8: Bare thermoformed panel (left), locally resonant metamaterial solution (center) and locally resonant metamaterial solution tuned to 156 Hz by means of a PMMA mass (right) [6].

### 4.4 Results

An experimental campaign to validate the potential of this panel to reduce the excitation of acoustic modes, is carried out on the KU Leuven SoundBox. This is a concrete acoustic cabin which can be closed by a front panel and which has its first acoustic mode at 156 Hz. Two cases are analyzed in this validation: (i) the bare panel and (ii) the locally resonant metamaterial panel, which are measured in clamped condition. The thermoformed panels are excited by a loud-speaker located 450 mm away from the panels and at the outside of the SoundBox. The SPLs are measured in the inside of the SoundBox by two PCB microphones type 378B20 and a root mean square (RMS) per frequency across the microphones is computed. The results shown in Figure 9 indicate that the SPL peak at 156 Hz present when the acoustic cavity is closed by the bare panel is reduced with 8 dB in case the cavity is closed by the locally resonant metamaterial solution, with a comparable SPL in the other frequency ranges. In this case, the resulting locally resonant metamaterial panel is 2.3% heavier than the original thermoformed panel. Furthermore, in a more recent developed design, the resonant inclusion is further optimized in order to enlarge the stop band width and a foam core is added to enhance the high-frequency NVH behavior of the panel, albeit at the cost of a larger mass addition. This results in a final locally resonant metamaterial solution with 7% of total added mass [6]. For a demonstration video about this application, the reader is kindly referred to the following link https://bit.ly/3cSdVrp.

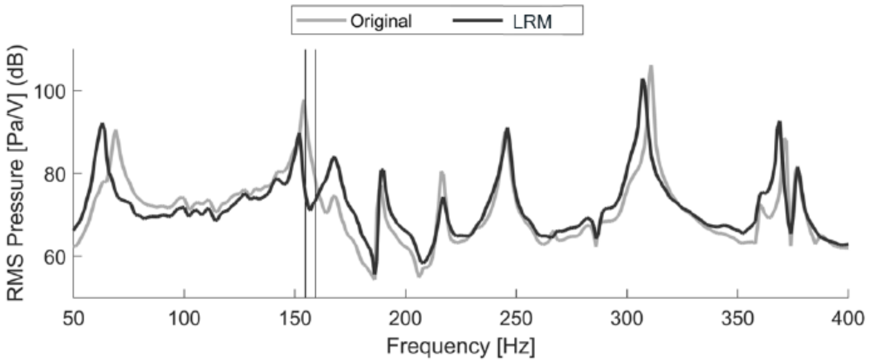

Figure 9: RMS of the frequency response function of the SPL measured for the original panel and the locally resonant metamaterial panel. The vertical lines represent the predicted stop band limits. The dB reference used is 2e-5 Pa [6].

## 5. CONCLUSIONS

This work presented three lightweight locally resonant metamaterial solutions applied to automotive applications to improve NVH behavior. The designed solutions are made of different materials by different production processes. Firstly, 3D printed patches were applied to a vehicle shock tower, which showed to mitigate the structure-borne noise due to acoustic tyre resonances in the passenger compartment of the vehicle similarly or even better as the current deployed solution in the vehicle, but only needed 52% of the mass of the current solution. Secondly, rubber resonant metamaterials that are produced by milling were applied to a tyre. The solution led to a strong NVH attenuation within the frequency range of the first acoustic resonances of the tyre and required a 5.4% of total mass addition to the tyre. Lastly, the locally resonant metamaterial concept was applied to thermoformed panels. The designed solution showed to reduce the excitation of the first acoustic mode of a cavity by 8 dB while adding 2.3% of mass as compared to the original panel.

## ACKNOWLEDGEMENTS

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