Chapter 12
Design and Testing of Vibroacoustic Metamaterials for Active Damping of Traffic Noises

W. Kaal, M. M. Becker, L. S. Kollmannsperger, and S. C. L. Fischer

Abstract Metamaterials take advantage of internal architecture to achieve functional integration and targeted property changes. Vibroacoustic metamaterials (VAMM), a sub-class of metamaterials, enable interaction with acoustic waves in different applications, inducing damping of specific frequency regimes through their geometrical architecture. To increase the functionality and flexibility of those materials, methods to actively trigger and shift regions of high damping are being developed.

In the present paper, recent advances in the design and characterization of active vibroacoustic metamaterial unit cells for traffic noise reduction will be presented, for example for noise protection in urban areas in cities or next to highways. According to literature, the noise spectrum of traffic noise spans the range of the hearable spectrum and varies according to the type of vehicle, their speed, their tires, the current road conditions and the weather. The two main influencing factors are the tire-road friction and the noise of the drive train. While there are efficient damping solutions for high frequencies, especially frequencies below 2 kHz are challenging to tackle with conventional materials. Additionally, the needed damping region may change according to the above factors and therefor active adaptation will improve the efficiency of damping.

For this reason, this study focuses on the design of two programmable VAMM (PVAMM), one whose range of action is tunable a-priori (passive VAMM) and another requiring an external trigger to be applied, in this case a change in the internal pressure (actrive VAMM). For the active VAMM, wood, a renewable raw material, is to be used as the base material. In order to fully understand the potential of the VAMM, experimental characterization was performed regarding vibroacoustic properties. For this purpose, the samples in this study are excited with an electrodynamic shaker and the structural response is recorded. The research aims to provide new concepts for metamaterials for noise reduction applications which can be scaled from laboratory experiments to industrial application.

Keywords Acoustic · Metamaterial · Damping · Noise · Testing

Introduction

In times when safety, comfort and environmental requirements are of equally great importance for the design of novel material solutions, engineers are faced with the challenge of developing components that meet these conflicting requirements. In the area of noise reduction, there are many scientific studies focusing on adverse effects of noise on human health [1, 2], showcasing the need for innovative material solutions for its mitigation.

Traffic noise is encountered in many different situations with varying loudness, exposure time and frequency spectrum: As a pedestrian on the side of the road, in a vehicle or for example in offices, schools or residential buildings that are in proximity to major roads. Every situation requires different approaches to mitigate or reduce the noise. Therefore, there is a

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great need for application-specific, customized solutions for different noise protecting applications such as noise in building and shielding residential areas from traffic noise (see Figure 1).

Traffic noise is a superposition of many individual sound emitters. The sound spectrum perceived is influenced, among many other factors, by the type of vehicles present, the number of vehicles and their speed, the distance to the road, the road type and its humidity [3, 4]. Generally, on dry asphalt roads, the peak intensity of traffic noise is in the frequency range between 500 and 1000 Hz, with buses and trucks contributing more to the lower frequencies and passenger vehicles to the higher frequencies [3]. However, presence of water on the road due to rainfall and other factors can shift the frequency spectrum quite drastically, e.g. with maximum intensities shifted from 1 kHz to around 3 kHz in the presence of water on a road as shown by Cai et al. [5]

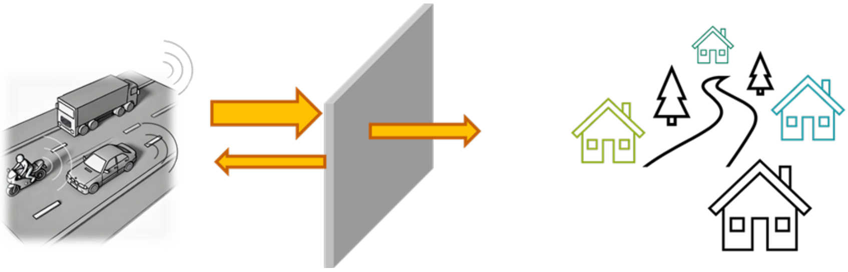


Fig. 1 Schematic representation of the requirements of noise attenuation materials

The simplest method of reducing noise and structural vibrations is to select suitable materials and components as large and heavy as possible. However, this is neither economically sensible nor ecologically sustainable. Vibroacoustic metamaterials (VAMM), a subclass of metamaterials [6], influence structure-borne sound propagation and sound radiation in a specified frequency range through annihilating interference and negative stiffnesses or masses [7]. They provide one approach to optimize acoustic properties through engineering of the geometry while minimizing the use of resources. These consist either of an array of distributed mass elements (Bragg effect) or of a basic structure with periodic local resonators [8]. Typical resonator designs are membrane-like structures [9], bending beams or columns [10]. The interaction of the structural vibration with the resonance vibration of the local resonators leads to specific stop bands with a high suppression of wave propagation [8]. The position and width of the stop bands in the frequency range can be influenced by the size of the unit cell incorporating the resonators, the effective resonator mass, the materials used and the structural properties, which allows great flexibility for application-specific customization.

Based on literature, it can be seen that a large number of VAMMs have already been developed [7,11–14]. These are generally designed as passive elements for a specific application so that a stop band occurs in a desired frequency range. However, it is known from the literature that the acoustic emission and the structural vibration of traffic noise are strongly dependent on external factors such as the type of vehicles, speed and atmospheric conditions. Active VAMM with tunable band gaps could provide an interesting new approach to integrate more functionality within a single material system. In previous works, the authors have demonstrated different passive and active VAMM concepts (see Figure 2). Kaal et al. [13] were able to demonstrate the variable damping behavior of a mechanical metamaterial under dynamic load. The cell showed lower damping at lower strains, whereas the damping increased significantly at higher strains. In addition, Kollmannsperger et al. [15] showed a concept for an inflatable VAMM unit cell with tunable band gaps based on applied air pressure.

This study focuses on the comparison of two designs of a programmable VAMM (PVAMM), one with a passive and one with an active noise damping integrated. First, the design of the two unit cells is presented followed by the characterization of the acoustic damping effects based on mechanical excitation in the frequency range relevant for traffic noise mitigation. For more detailed information and further characterization results on the individual unit cells, we refer the reader to our original publications [14, 15]. Finally, both designs will be discussed in terms of advantages and disadvantages to consider for application in traffic noise mitigation.

Materials and Methods

Vibroacoustic metamaterials can be designed in various different ways. To showcase the potential for application for traffic noise reduction, two concepts are presented and characterized in this paper (see Figure 3):

- An active, inflatable VAMM manufactured from wood and silicone sheets and including a steel mass
- A passive VAMM manufactured by laser-powder-bed fusion with integrated powder

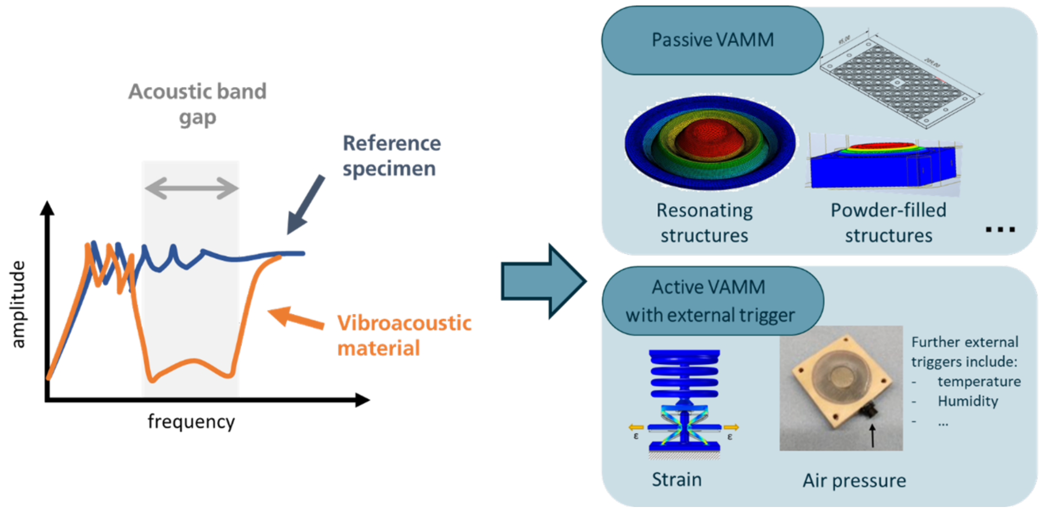


Fig. 2 Vibroacoustic metamaterials: Properties and classification of PVAMM

Unit cell design 1: Active VAMM

In order to demonstrate the usability of wood as a renewable raw material in the field of vibroacoustic metamaterials and the adjustability of damping ranges using an external trigger, a demonstrator unit cell is being constructed. The basic structure of this cell consists of a 9 mm thick wooden panel with a recess in the middle. A conical steel mass weighing 27.9 g is inserted concentrically into this recess. The individual components are bonded together with a 1 mm thick silicone mat. The additional attachment of a valve, which is directly connected to the recess, allows the pressure within the unit cell to be regulated. A more detailed overview of the unit cell and further measurements can be found in a proceedings publication by Kollmannsperger et al. [15].

Unit cell design 2: Passive VAMM

In order to demonstrate a passive monolithic VAMM concept, an array of resonant cavities was designed. The cavities can additionally be filled with powder to enhance the damping through powder motion and frictional effects. The passive vibroacoustic plates were fabricated by selective laser sintering (EOSINT P395 system by EOS GmbH, Krailing, Germany) with polyamide powder (PA 2200). Three plates of identical outer dimensions of 210 mm × 95 mm × 5 mm were fabricated: A fully sintered plate, a plate with empty resonators and a plate with powder-filled resonators. The two later resonators comprise 44 local resonators with a spacing 19 mm. A more detailed overview of the unit cell and further measurements can be found in a publication by Kollmannsperger et al. [14].

Experimental characterization

The acoustic properties with regard to sound transmission and the vibromechanical properties of the two VAMM were investigated experimentally using an electrodynamic shaker (vib TV52122-M, TIRA GmbH, Schalkau, Germany). The VAMM specimen were excited with broadband white noise in two frequency ranges, notably between 0 - 300 Hz for the active VAMM and 0 - 5000 Hz for the passive VAMM. For the active VAMM, the internal pressure was varied between 0 and 0.75 bar using a hand driven airpump.

Analysis

Experimental validation of the active VAMM

By evaluating the force and acceleration signals in the frequency range, the characteristic transfer function of the cell was determined for each internal pressure (see Figure 4). A shift of the maximum and minimum of the measurement curves to higher frequencies with increasing internal pressure of the cell can be recognized both from the observation of the amplitude and from the observation of the phase. This shift is directly accompanied by a shift of the stop band to higher frequencies. The sharpness of the transition from the maximum to the minimum of the amplitude and the depth and width of the negative peak

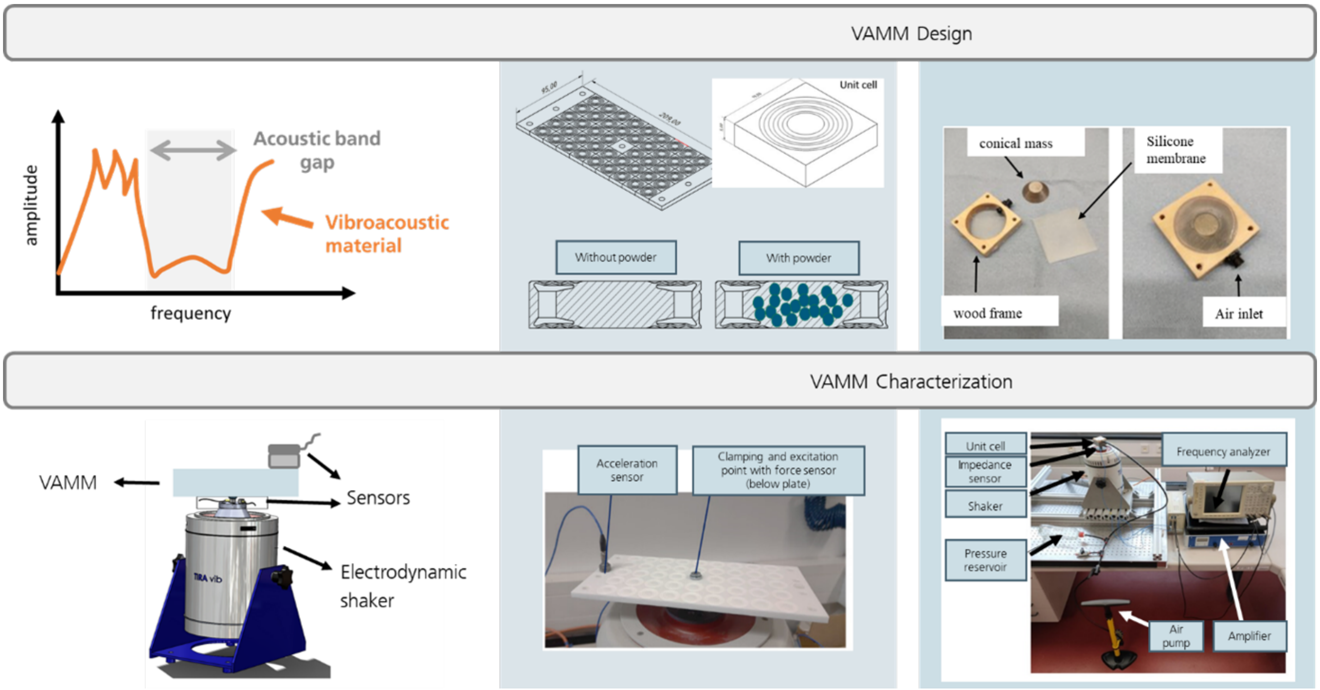


Fig. 3 Design and characterization of two VAMM unit cells: Passive unit cell manufactured by laser powder bed fusion with embedded powder cavities and active inflatable wood-silicone composite with tuneable properties by air pressure

in the observation of the phase can already be used to qualitatively recognize the attenuation properties. The more blurred the transition from the maximum to the minimum of the amplitude of the transfer function and the flatter the negative peak of the phase, the greater the effective attenuation of the PVAMM.

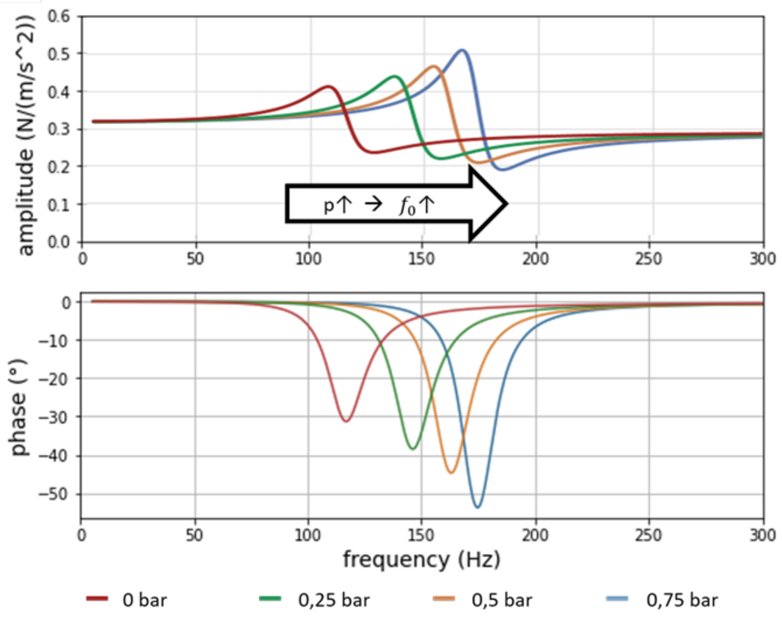


Fig. 4 Experimental characterization of the active VAMM unit cell as a function of air pressure. A) Amplitude as a function of frequency b) Phase as a function of frequency. The figure is adapted from [15].

The experimentally determined transfer function of the unit cell was used for comparison with an analytical four-parameter model (see Figure 5). This model consists of a spring with stiffness k, a damper with damping constant d and two masses (m1 and m2).

In this way, the effective stiffness k and the effective dimensionless damping ratio D of the unit cell could be quantitatively determined as physical parameters for each measurement. Finally, a value for the stiffness and damping can be assigned to each internal pressure using suitable interpolation. Figure 5 shows that the effective damping decreases with increasing internal pressure from 8 % at 0 bar to 4 % at 0.75 bar, whereas the effective stiffness increases from 13 Nmm^{-1} to 32 Nmm^{-1}. By comparing the measured values with the analytical model, the frequency shift can also be quantified, so that an increase in the internal pressure by 0.75 bar results in a frequency shift of 57 Hz.

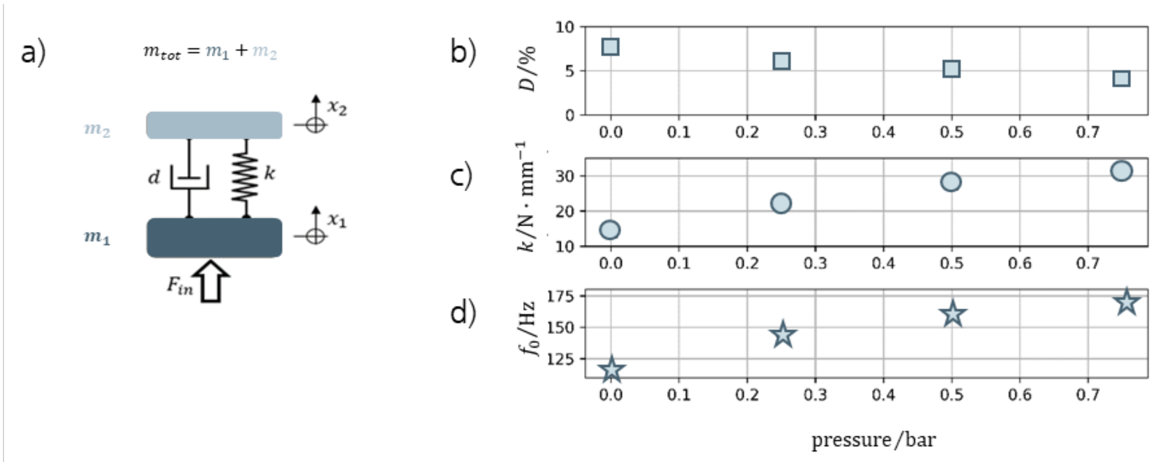


Fig. 5 Analytical description and modelling of the active VAMM unit cell. a) Mathematical model based on two masses, a spring and a damper. Determination of b) the effective damping, c) effective stiffness and d) resonant frequency based on the analytical model. The figure is adapted from [15].

Experimental validation of the passive VAMM

In the following section, the vibrational properties of the passive VAMM are described (Figure 6). The plates were excited with broadband noise and their vibrational response measured. Below 700 Hz and above 3 kHz, the three samples exhibit similar response to excitation. Between 700 Hz and 3000 Hz, the VAMM plates with and without powder exhibit a band gap with an average damping of the amplitude by 20 dB. While the powder-filled VAMM plate exhibits maximum acoustic damping in this frequency range, it can be observed that the air-filled plate actually has a wider band gap and more pronounced attenuation at higher frequencies starting from around 2200 Hz.

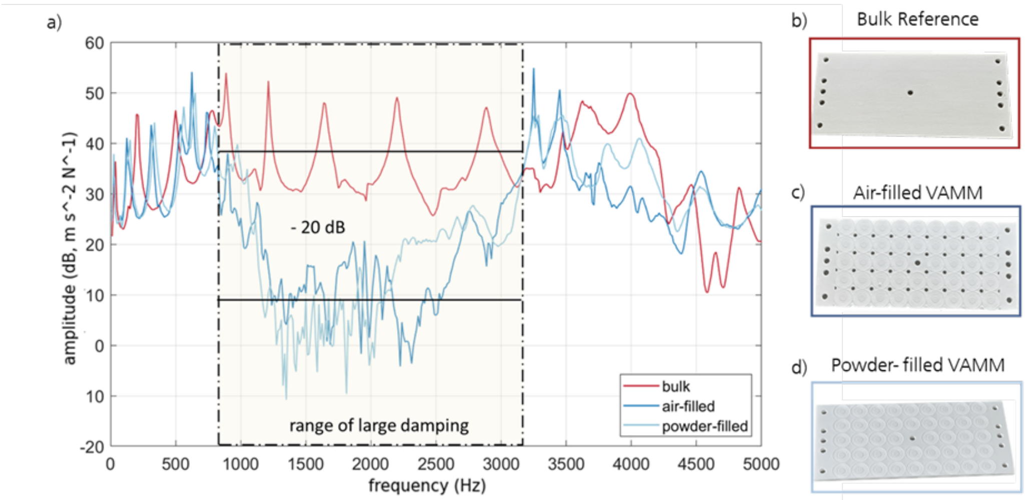


Fig. 6 Experimental characterization of the passive VAMM. The figure was adapted from Kollmannsperger et al. [14] with permission from Wiley.

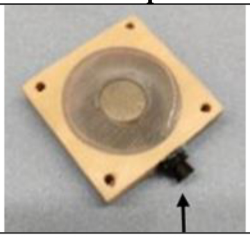
Discussion of application of passive and active VAMM in traffic noise control

Vibroacoustic metamaterials offer promising advantages for traffic noise mitigation. One key advantage is their ability to achieve superior sound attenuation compared to traditional materials, particularly in specific frequency ranges like low-frequency noise, which is a significant component of traffic noise. They can be designed to target and reduce particular noise frequencies while maintaining a lightweight structure, making them more efficient and adaptable. Additionally, these materials can be tailored for specific environmental and structural requirements and tunability, providing flexibility in design and application.

However, there are also disadvantages to consider. Vibroacoustic metamaterials can be more complex and costly to produce compared to conventional noise barriers, which may limit their widespread adoption. The performance of metamaterials may also be sensitive to environmental factors, such as temperature or wear over time, potentially reducing their effectiveness in long-term outdoor applications. Moreover, the current stage of research and development may mean that extensive testing is still needed before these materials can be broadly implemented for traffic noise mitigation.

As a summary, the two studied metamaterial types are compared side to side in Table 1 concerning the studied acoustic band gap, advantages and disadvantages in the application for traffic noise mitigation.

Table 1 Comparison of the active and passive VAMM concept for application in the area of traffic noise reduction

	Active VAMM concept	**Passive VAMM concept**
Design		
Band gap	- Band gap tunable - Range from 125 to 180 Hz	- Band gap preprogrammed - Range from 750 Hz to 3 kHz
✚	- Tunable band gap by air pressure - Changing mass and membrane enables tuning of VAMM unit cell without geometrical change - Production can be scaled - Enables layerwise production techniques - Use of wood as base material successful	- No infrastructure needed - Good recyclability due to use of only one single feedstock; possibly the VAMM could be reused to manufacture powder again - Lowered chance of local production defects due to one-material-build
▬	- Air pressure providing infrastructure needed - Energy needed to operate the active switch of properties - VAMM complex to recycle - High complexity of the multi-dimensional design-space complicates the computer aided development	- Preprogrammed acoustic damping band gaps - Production of the VAMM requires LPBF machine and handling of powder - Production is relatively slow - Limited design-space due to small amount of possible materials and so limited space of specific density

Conclusion

The approach shows that it is possible to design VAMM concepts with stop bands in the frequency range relevant for traffic noise and the active VAMM concept can be adapted to changing environmental conditions using external triggers. In the future, the unit cells can further be optimized by experimental and numerical methods. Larger scale prototypes will enable the effect of the material systems in application like - scenarios. Both passive and active VAMM concepts can be scaled to different applications, however, the specific requirements regarding present infrastructure and energy consumption will then determine which concepts are most viable.

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