Application of vibroacoustic metamaterials for broadband vibration reduction on space structures

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Abstract

In this paper, vibroacoustic metamaterials are applied for launcher structural components made of composite materials to optimize their vibration transmission characteristics. For these applications the stopband behavior is desired in the frequency range up to 200 Hz and a broadband damping characteristics up to 500 Hz. A stab-like resonator concept is considered to fulfill the requirements on high damping and low additional mass to the component. Dispersion relations of the unit cell are calculated to predict the stopband region in an infinite compound. The resonator is designed and built to have its relevant out-of-plane resonance frequency at 160 Hz. The validated design of resonator is transferred to finite planar specimen made of carbon fiber reinforced polymers (CFRP) to evaluate the stopband behaviour of the vibroacoustic metamaterials. The expected dynamic behaviour is observed in the experimental investigation as well as in the simulation, thus proving the potential of the usage of vibroacoustic metamaterials for dynamically optimized launcher structures.

Introduction

In the space industry, more and more launcher components made of metallic materials are being replaced with composites ones as carbon fiber reinforced polymers (CFRP). For example, The European Space Agency (ESA) aims to develop a black upper stage for the new generation of Ariane 6 by 2025, with an objective to increase the payload capacity by two metric tonnes [1]. Though these materials have higher stiffness-to-mass ratio compared to metals, they also lead to high vibration levels. These vibrations can become critical especially in the launch phase. An innovative approach to reduce vibrations are vibroacoustic metamaterials.

Vibroacoustic metamaterials are usually formed of multiple periodically arranged unit cells – the smallest identical part of the base structure with a resonator on it. The local resonators are specifically placed on the subwavelength scale of the incident wave. They are tuned for a resonance frequency, at which vibration attenuation is required. Interaction between local resonators and the travelling wave leads to a stopband – a frequency region with a high vibration attenuation. For the time being, the potential of vibroacoustic metamaterials has been recognized both for aeronautics [2] and space [3], where they have been introduced on the payload fairing.

In this paper, the research towards application of vibroacoustic metamaterials in composite upper stage of a conceptual Ariane 6 launcher has been performed. This includes the conceptual design of unit resonators, choice of the most suitable concept. This unit resonator was then built and investigated experimentally. In the next step multiple resonators have been applied to a CFRP plate to analyze the dynamic behaviour in the finite component. The favored design is then applied to a CFRP-cylinder to represent a scaled upper stage of a launcher.

Requirements and design approach

Vibration reduction on the launcher's structure with vibroacoustic metamaterials occurs on the upper stage component of a conceptual Ariane 6 launcher, being currently developed at MT Aerospace AG [4]. The finite-element (FE) model of the launcher's structure from a preceding concept study is displayed in Figure 1.

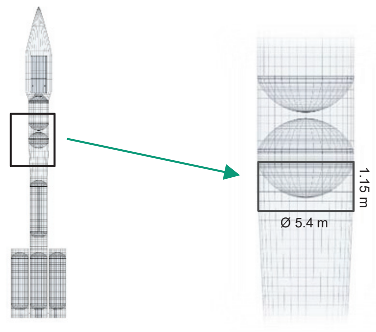

Figure 1: FE-Model of a conceptual Ariane 6 with the target upper stage (MT Aerospace AG)

The relevant requriements on vibration reduction measure are listed in Table 1

Table 1: Requirements on the dynamic behaviour of the target component

Requirement	*Description*
Frequency range for stopband	Up to 200 Hz
Vibration reduction range	Broadband up to 500 Hz
Additional mass	Max. 20 % of reference structure

The design process of vibroacoustic metamaterials can be represented as shown in Figure 2.

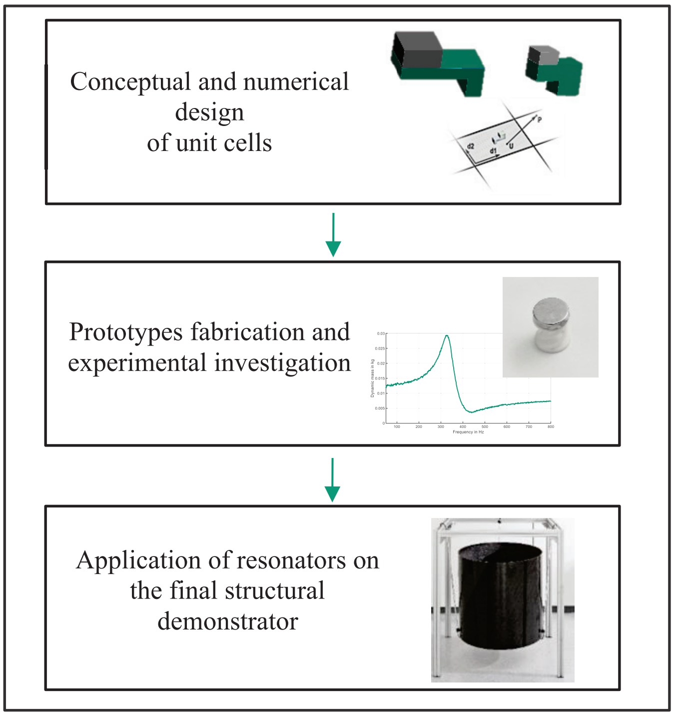

Figure 2: Design process of vibroacoustic metamaterials

Concept design

For the specific application of vibroacoustic metamaterials for launcher's interstage components, the required vibration attenuation is broadband with low additional mass. That is why, the resonator concept with high damping properties has been chosen from multiple considered concepts. The concept is shown in Figure 3 and represents a stab-type resonator. It consists of hollow cylinder made of polyurethan to represent the spring element and an additional metallic mass to represent the mass element.

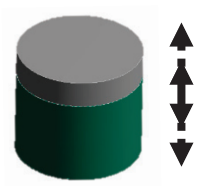

Figure 3: Favored stab-type resonator concept

The resonance frequency of mass-spring-system is then determined by longitudinal stiffness of the spring element and additional mass of metallic element to be at approx. 160 Hz.

Numerical Investigation

The effect of vibroacoustic metamaterials on the dynamic behaviour is evaluated numerically in following steps:

- Calculation of dispersion relations for infinite structures for the identification of the stopband location on the unit cell level,
- Calculation of transfer function with applied resonators (18 % additional mass) on a planar CFRP-specimen to evaluate the vibration reduction behavior on a finite structure,
- Calculation of transfer function with applied resonators (18 % additional mass) on a cylindric CFRP-specimen as scaled demonstrator of the upper-stage.

A unit cell modelling approach is used to analyse the wave propagation in the proposed two-dimensional periodic metamaterial structures. This approach allows the investigation of characteristic dispersion curves in periodic structures by means of a single unit cell. These have been calculated analogous to Claeys [5]. Figure 4 shows the unit cell geometry and its dispersion relation for the stopband identification in ideally undamped case. The stopband is observed starting from the resonator's out-of-plane frequency at approx. 162 Hz till 178 Hz. The effective to total mass ratio is 15.8 % for this concept.

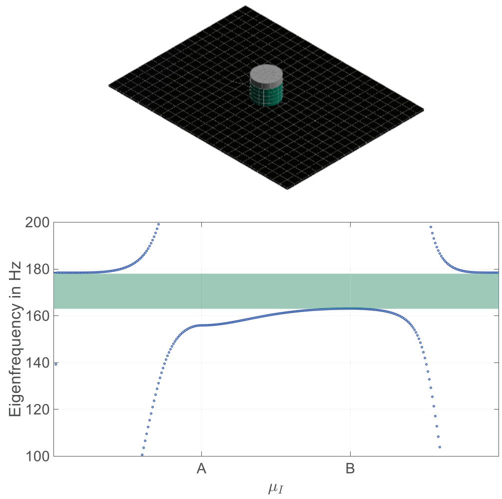

Figure 4: Dispersion relation of the stab-type resonator concept

The resonators' geometry has been firstly designed according to material characteristics specified by manufacturers. They have been validated and adjusted in agreement with experiments. Also the damping factor has been determined, resulting in high damping ratio of 14 % for polyurethan material. The geometry of the unit resonator is then adjusted to meet the prescribed resonance frequency.

In the next step, a finite CFRP plate has been built up to investigate the dynamic behavior of finite compound. To meet the requirements on subwavelength scale and the additional mass, nine resonators have been placed on the specimen plate. The demonstrator plate and the set-up for numerical simulation are shown in Figure 5. Harmonic analysis using Finite-Element-Method has been performed to evaluate vibration reduction performance of vibroacoustic metamaterials.

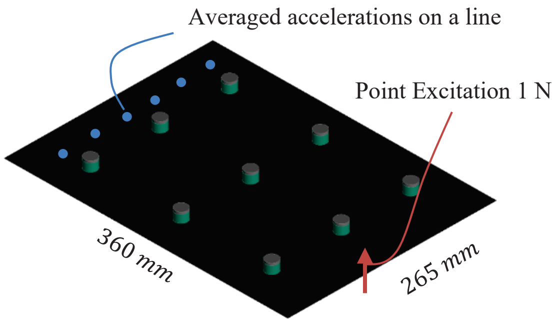

Figure 5: Numerical set-up of the finite CFRP specimen with nine local resonators

The amplitude responce functions of the reference bare plate and vibroacoustic metamaterial plate evaluated on a line are shown in Figure 6.

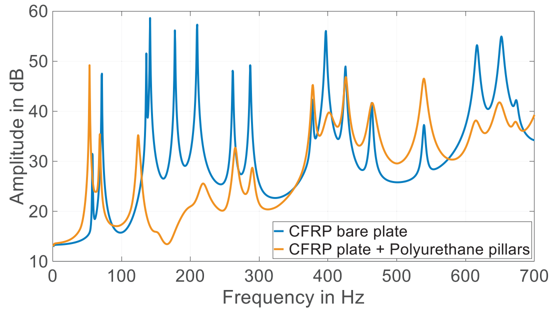

Figure 6: Simulation result of amplitude response functions of a bare and metamaterial plate

A vibtation reduction up to 30 dB is observed starting from resonators‘ eigenfrequency at around 160 Hz lasting till 220 Hz. Due to high damping the stopband appears to be even wider. Furthermore, amplitude reduction up to 15 dB is also observed for following modes after 220 Hz. This evaluation shows the desired broadband vibration reduction for the launcher’s upperstage use case.

Experimental Investigation of the CFRP metamaterial plate

The vibration reduction behaviour of vibroacoustic metamaterials has been experimentally investigated on planar specimen. The experimental set-up was realized similar to simulation, hanged out with elastic ropes to approximate free-free boundary conditions. The excitation has been realized with a shaker, positioned in accordance with excitation in the simulation. The line frequency response function has been measured using 1D Laser Scanning Vibrometer. Figure 7 shows the built demonstrator as well as experimental transfer function for the base plate and vibroacoustic metamaterial plate.

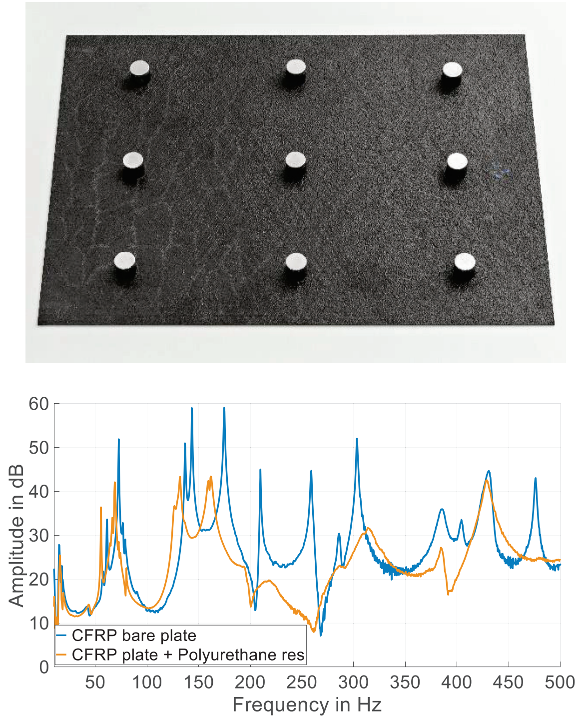

Figure 7: Vibroacoustic metamaterials CFRP demonstrator and the transfer function from experiment

A vibration reduction behaviour is observed in the experimental investigation as well, demonstrating slightly different effects compared with the numerical results. In the experiment, the stopband appears from approx. 175 Hz and lasts until 250-270 Hz, demonstrating even wider vibration reduction with the amplitude difference up to 30 dB. The discrepancy in the results can be traced back to a big influence of adhesive on the elastomeric elements. Retrospectively it could be observed, that adhesive alters material characteristics of elastomer towards more stiff and brittle behaviour. Aspects of manufacturing and assembling have to be taken into account more sharply in the future design. Nevertheless, global damping effect has been observed in the experiment for a wide frequency range as well, demonstrating amplitude reductions up to 20 dB. Thus, this approach is proved to be a beneficial hybrid solution (stopband region for narrow frequency range and high damping for wide frequency range) for vibration reduction in space applications.

Numerical investigation on cylindrical CFRP demonstrator

In the final stage, the updated concept of stab-type resonator is applied to a cylindrical CFRP Cylinder to represent a called upperstage component of the conceptual Ariane 6 launcher. The simulation set-up and transfer function are shown in Figure 8.

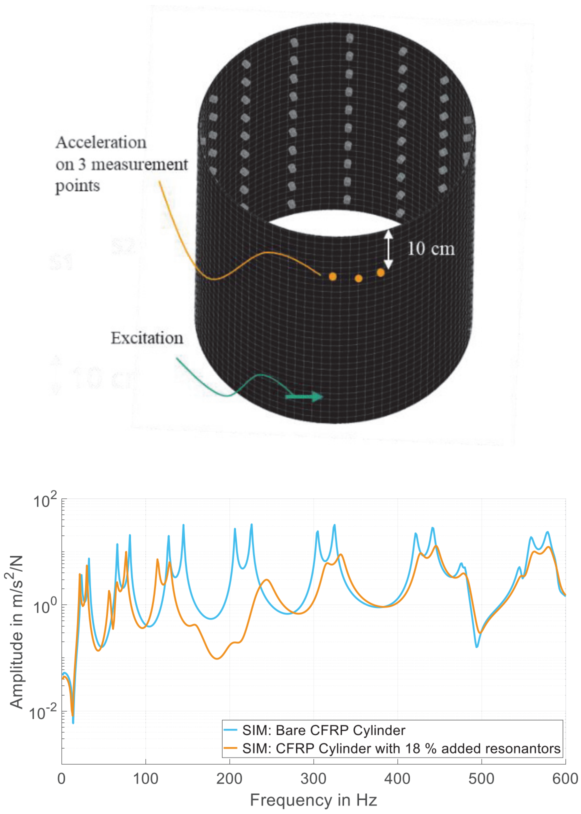

Figure 8: Numerical model and transfer function of the scaled CFRP cylinder

The updated material parameters for resonators lead to stopband starting at approx. 175 Hz, continuing to 220 Hz and again demonstrating further broadband damping in higher frequency regions. This set-up will be implemented experimentally and has the aim to confirm the high potential of vibroacoustic metamaterials for launcher components.

Conclusions and Outlook

In this paper, conceptual and numerical approaches for design of vibroacoustic metamaterials with high damping properties have been described. For the challenging requirements of high damping, low target frequency and low additional mass, the combination of numerical analysis based on unit cell modelling and finite element simulations give a comprehensive insight on the resulting vibration behaviour. For the favored concept of a stab-type resonator a desired vibration attenuation (up to 30 dB in the stopband region and up to 20 dB in the wide frequency range up to 500 Hz) has been demonstrated.

The results have been presented for CFRP plate experimentally and for cylindrical scaled upper stage numerically. In the next phase, the knowledge gained from simulations and experiments will be transferred to a cylindrical scaled upper stage component, to achieve the desired vibration reduction behavior experimentally.

Literature

[1] European Space Agency (ESA), „ Available: https://www.esa.int/Enabling_Support/Space_Transportation/Contracts_signed_for_prototype_of_a_highly-optimised_black_upper_stage.,“ 2019. [Online].

[2] G. Palma, H. Mao, L. Burghignoli, P. Göransson und U. Iemma, „Acoustic Metamaterials in Aeronautics,“ *applied sciences,* 2018.

[3] K. Egashira, K. Fukaya, K. Mori und T. Takahashi, „Application of acoustic metamaterial with stopband to panel and cylinder,“ in *INTERNOISE 2016*, Hamburg, Germany, 2016.

[4] MT Aerospace AG, „LOKI (Leistungsanalyse, Options- und Kostenbewertung für innovative Strukturkonzepte eines ARIANE-Nachfolgers) Förderkennzeichen 50RL1132,“ Augsburg, 2016.

[5] C. Clayes, „Design and analysis of resonant metamaterials for acoustic insulation,“ KU Leuven, 2014.