Design of an Innovative Acoustic Metamaterial

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Abstract: - This report presents the design of an innovative acoustic metamaterial, in particular the design of a negative stiffness element that can attenuate the vibration level in a wide range of frequencies. The theoretical basis for the design of the metamaterial is the concept of negative stiffness, in the sense that the slope of the force-displacement diagram for the particular metamaterial becomes approximately zero. This has significant advantages as a zero stiffness element cannot transfer vibrations at any frequency. The downside of many zero stiffness elements is that they cannot carry any dead load. As will be shown in this study, this is not the case for the particular metamaterial. A prototype of this metamaterial has been produced using HDPE and tested under different conditions. The numerical results and experimental measurements demonstrate its intended behavior and provide a basis for further improvements and optimization.

Key-Words: - acoustic metamaterial, finite element, modal analysis, zero stiffness

1 Introduction

The increasing energy prices and the environmental impacts of pollution on the world's average temperature require the development of environmentally friendly and energy efficient technologies. In different domains including transportation, robotics and infrastructure the development of lightweight materials and lightweight structures remains the most direct and effective way for contributing positively in the reduction of energy consumption and emission of harmful gases and particulate matters. The main two challenges in the development of such materials and structures is structural performance and vibrations. The material or the structure needs to withstand the loads exerted on the structure. Therefore detailed design using finite element analysis and sound engineering are required for minimizing the weight. For the vibrations it is required to dissipate the vibration energy using dampers (shock absorbers) or mounts made out of viscoelastic material. The first solution is labor intensive and more complex from a system point of view. The second one can only produce a finite energy loss and at particular frequencies.

Different methods have been proposed up to now to solve structural problems with stress, displacement, buckling and frequency constraints. The finite element method in combination with optimization algorithms provide a strong basis for designing materials or structures that can fulfill multiple criteria including broad band vibration suppression. The role of numerical optimisation and of the optimisation algorithm is of paramount importance in finding an optimal solution or even a solution that can fulfill the multiple and sometimes conflicting criteria e.g. reduced mass but increased vibration suppression.

In this paper, for the first time, a prototype acoustic metamaterial is presented. The acoustic metamaterial is characterized by broadband vibration suppression. As will be shown, the design of the acoustic metamaterial is not based on a mathematical formulation but on the basis of functional description of its structural elements. The prototype metamaterial is designed using a CAE software, SolidWorks, and then studied in a finite element software, ANSYS Educational. The detailed response of the material is analysed, where the approximately zero stiffness of the material is observed. Furthermore, a modal analysis revealing the natural frequencies of the material as well as a frequency response analysis are conducted, in which we observe the vibration amplitude attenuation for a wide range of frequencies.

The rest of the paper is structured as follows: In Section 2 the CAE model of the metamaterial is shown and a functional description of its elements is provided. In Section 3 the Finite Element model of the material is described and numerical results with respect to its behavior under static and dynamic loads are illustrated. In Section 4 the behavior of the real prototype material is presented and discussed in relation to the numerical results. Finally in Section 5 conclusion are drawn.

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2 Functional description

An image of the proposed metamaterial is shown in Figure 1. The metamaterial consists of 6 different types of elements.

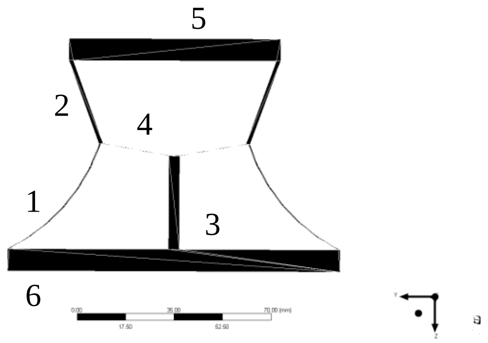

Fig 1. View of the metamaterial structure

Element 1 is being used as a flexible element that deforms during the application of a load on element 5. The contact area between element 1 and element 6, the latter being the support of the structure, is increasing with increased loads. As the contact between element 1 and element 6 increases the angle of element 1 with respect to the horizontal changes and becomes more vertical. Elements 2, 4 and 5 form a flexible spring of Beleville type that is used to reduce the stiffness of the metamaterial, following the application of an initial load. Elements 4 buckle under the application of an external load at 5 and constitute the main mechanism for reducing the stiffness of the metamaterial at higher loads.Element 3 is used to support the structure and restrain the further motion of point 5 at increased loads. Elements 3, 5 and 6 are considerable stiffer than elements 1, 2 and 4. By varying the thickness of the different elements the response of the force displacement diagram changes and thus different vibration attenuation characteristics may be obtained. In this study, the results for a particular design are presented; optimization of the total response can be of course further refined.

The reduction of the vibration level for a large range of frequencies is based on the following equations:

$$m \cdot \ddot{x} + c \cdot \dot{x} + \mathrm{k} \cdot x = F \quad (1)$$

where m is the mass of the component, c is the damping coefficient, k is the spring constant and F the external load.

For simplification reasons and under the assumption that only Rayleigh damping is present we assume that $c = 0$. The external load is assumed to be a sinusoidal one:

$$F = F_{st} + F_0 \cdot sin(\omega \cdot t) \quad (2)$$

where F_{st} is the static component of the external force and F_0 is the amplitude of the dynamic component of the force, ω is the frequency of excitation and t is time.

By combining Equations (1) and (2) we get:

$$m \cdot \ddot{x} + \mathrm{k} \cdot x = F_{st} + F_0 \cdot sin(\omega \cdot t) \quad (3)$$

Equation (3) can be split in two parts, the first one describing the static behaviour of the metamaterial:

$$k_{st} \cdot x = F_{st} \quad (4)$$

and the second one the dynamic one:

$$m \cdot \ddot{x} + k_{dyn} \cdot x = F_0 \cdot sin(\omega \cdot t) \quad (5)$$

under the assumption that

$$k = k_{st} + k_{dyn} \quad (6)$$

If the metamaterial is designed in such a way that the static spring component supports the dead load

$$k_{st} = F_{st}/x_{st} \quad (7)$$

where x_{st} is the spring deformation under the static load F_{st}. Now if k_{dyn} is designed such as $k_{dyn} \approx 0$ then Equation (5) is written as:

$$m \cdot \ddot{x} = F_0 \cdot sin(\omega \cdot t) \quad (8)$$

$$\ddot{x} = (F_0/m) \cdot sin(\omega \cdot t) \quad (9)$$

Thus with the vibration level is reduced by a factor m, there is no resonant frequency and most important the vibration attenuation holds for a vast range of frequencies.

3 Finite Element Analysis

The proposed metamaterial was evaluated in ANSYS Workbench Educational under static and dynamic loads. In the case of static loads linear and nonlinear analyses were conducted. The nonlinear analysis was merely a large deformation analysis that takes into account the change in geometry, in particular that of element 1, into account. For the dynamic analysis a modal analysis and the frequency response diagram for the metamaterial were derived.

3.1 Static load: Linear analysis

The results of the static load – linear analysis is shown in Figure 2. As may observed the geometry of the structure changes under the application of an external load, please refer to Figures 1 & 2. However, since this is a linear analysis this is not taken into account. Therefore, a nonlinear geometric analysis is required.

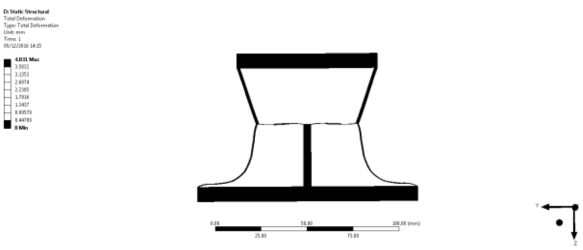

Fig 2. Linear analysis results for static load F_{st}

3.2 Static load: Nonlinear geometric analysis

The results of the static load – nonlinear analysis is illustrated in Figure 3. Clearly, the contact area between elements 1 and 3 has increased and this influences the effective stiffness matrix of the component. A force-displacement diagram, that presents the dependence of the component force developed in surface 6 versus the displacement at surface 5 is illustrated in Figure 4. The data are presented in Table 1. As observed in Figure 4 the slope of the force-displacement curve for a displacement $x = 15\ mm$ is approximately equal to zero and therefore the material has $k_{dyn} \approx 0$ at this operating region.

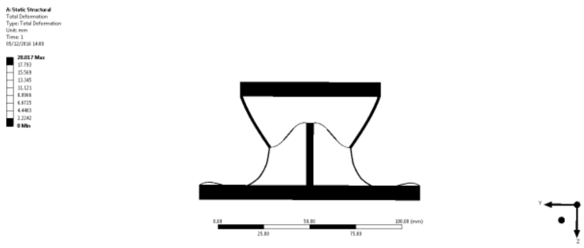

Fig 3. Nonlinear geometric analysis results for static load F_{st}

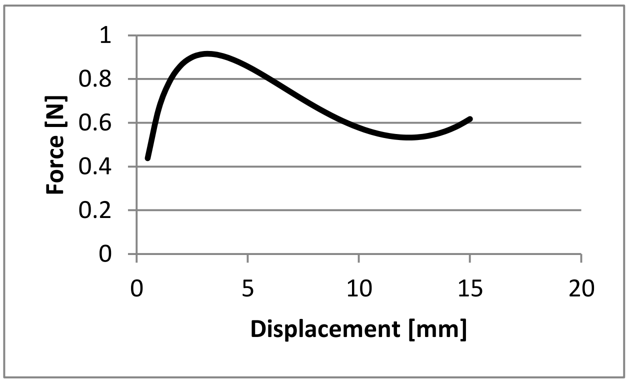

Fig 4. Nonlinear static analysis: Force displacement graph for the proposed metamaterial

Table 1 Nonlinear static analysis: Force – displacement data for the proposed metamaterial

Displacement [mm]	**Force [N]**
0.5	0.43772
1	0.66405
1.5	0.7911
2	0.86262

2.5	0.89973
3	0.91419
3.5	0.91315
4	0.90133
4.5	0.88197
5	0.8574
5.5	0.82937
6	0.7992
6.5	0.76796
7	0.7365
7.5	0.70554
8	0.6757

3.3 Dynamic load: Modal analysis

The results of the modal analysis are listed in Table 2, where the first six eigen-frequencies in the vertical direction are provided.

Table 2 Modal analysis results for the proposed metamaterial

Mode Number	Frequency [Hz]
1	24.288
2	27.72
3	78.686
4	84.444
5	114.11
6	332.75

From the 6 identified frequencies only modes 3 and 6 are considered to be relevant to the application, where surface 5 remains horizontal during the application of the external load. The three modes are illustrated in Figures 5 and 6. As observed mode 3 is very relevant to the deformation of element 1 in the vertical direction, while mode 6 is relates to the vibration of elements 1 in the horizontal direction.

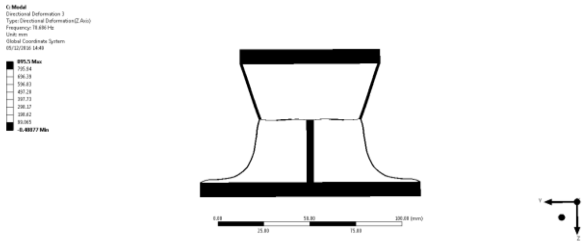

Fig 5. Deformation pattern for mode 3

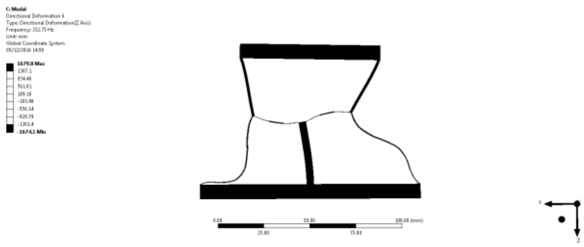

Fig 6. Deformation pattern for mode 6

3.4 Dynamic load: Frequency response analysis

A frequency response analysis was conducted. In particular the frequency response for a sinusoidal load on surface 5 was determined. Figure 7 plots the ratio of output over input amplitude versus the excitation frequency. As observed the ratio is constantly below that corresponding to the static load, $\omega = 0$. Thus, it can be concluded that the vibration level is attenuated for wide range of frequencies, thus achieving the design goal of broadband vibration attenuation.

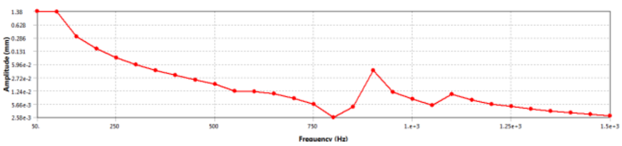

Fig 7. Frequency response in the frequency spectrum 0-1500 Hz.

4 Experimentally verified mechanical behavior of the metamaterial

A real prototype of the proposed metamateria was produced. The material from which it was made from was HDPE. A picture of the prototype is shown in Figure 8.

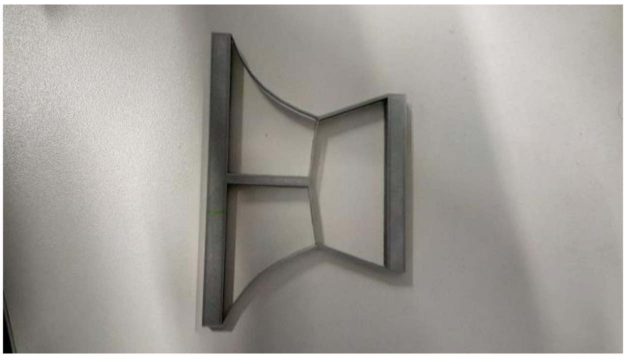

Fig 8. Real prototype of the proposed metamaterial

To evaluate the mechanical performance of the protorype in real conditions and compare the mechanical behaviour observed in simulation, the component was subjected to an external force, against a fixed wall. Figure 9 and 10 illustrate the mechanical test conducted.

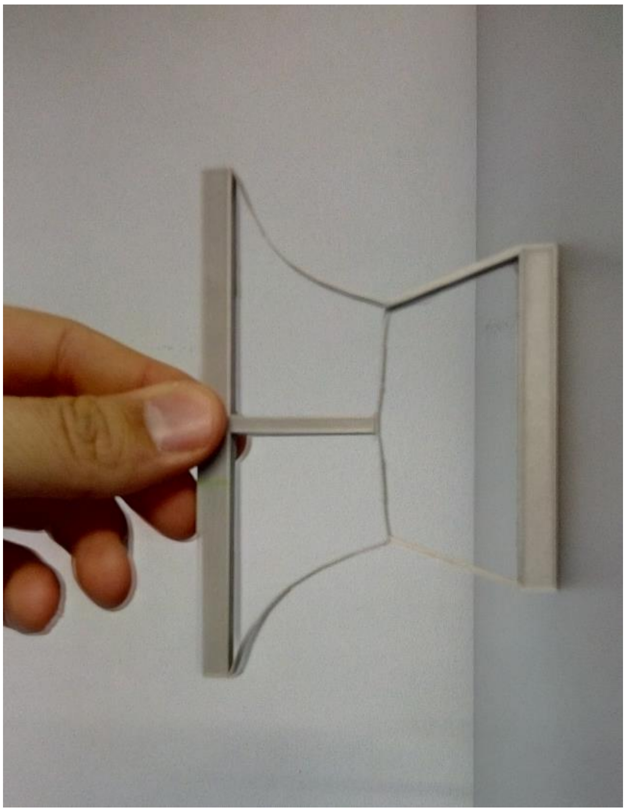

Fig 9. Metamaterial position prior to the execution of the experiment

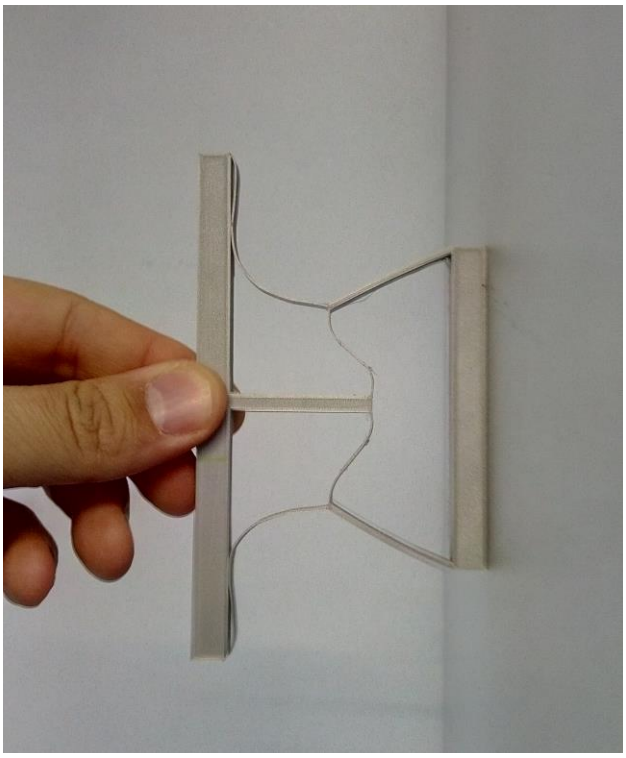

Fig 10. Metamaterial deformed position posterior to the execution of the experiment

As observed from Figures 3 and 10 the experimentally verified mechanical behaviour and the numerical results are aligned. It is highlighted that the contact area between elements 1 and 6 has increased and that elements 4 are deformed in exactly the same pattern. Thus, it can be concluded that the numerical results are accurate and the numerical model validated.

5 Conclusions

In this study the design of a novel acoustic metamaterial is presented. The proposed metamaterial is based on the concept of zero stiffness, where no vibrations can be transferred due to the extremely low equivalent spring constant of the structure.

The structure of the proposed metamaterial was developed based on the functional analysis of its parts, rather than on a finite element model.

However, its mechanical behavior under static and dynamic loads was studied in detail using the finite element software ANSYS Workbench Educational. In particular, the nonlinear mechanical behavior under static loads was investigated as well as a modal and frequency response analyses were conducted. The results of the nonlinear mechanical analysis show that indeed the metamaterial presents zero stiffness at increased static loads. Furthermore, the frequency response showed the effective vibration suppression for a wide range of frequencies as the ratio of output over input amplitude is always lower than that for zero frequency. Finally, the mechanical behavior of a real prototype of the metamaterial was tested. The measurements and the deformation pattern confirm the numerical results.

In the future, a more detailed investigation using state of the art modeling and optimization techniques will be conducted.

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