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In-vacuo structured fabrics for vibration control

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Abstract. This paper presents a study on a new tuneable material for vibration control purposes. The material is formed by a structured fabric wrapped in a deflated bag. The fabric is made of an interwoven mesh of rigid truss-like particles. The vacuum inside the casing produces a jamming effect. Hence, the elasticity and damping of the packaged fabric can be tuned by changing the level of vacuum in the bag. This material can be conveniently employed to develop new vibration control treatments and devices. In this respect, the paper first presents the tests carried out with a six-point bending machine to characterise the static and dynamic stiffness of the material as well as its damping properties. Then it demonstrates an application, where the material is used as a tuneable vibration absorber.

Introduction

The material considered in this paper presents is formed by a structured fabric wrapped in a vacuum casing [1]. The fabric is made by an interwoven mesh of rigid truss-like particles, which forms a loose flexible construction, such as for example a chain mail armour. The fabric is packaged into a deflated plastic bag, whose level of vacuum is controlled online with a micro-compressor. The vacuum generated inside the casing produces a jamming effect, which results from both interlocking and friction between neighbouring particles [2]. In this way, the elasticity and damping of the packaged fabric can be conveniently tuned by changing the level of vacuum in the case. The result is thus a tuneable lightweight material, which can be effectively employed to develop new treatments, e.g., tuneable liners, and devices, e.g., Tuneable Vibration Absorbers (TVA), for passive and semi-active vibration and noise control [3,4].

Material layouts and test facilities

This paper presents two types of experiments on prototype beam-like in-vacuo structured fabrics, which, as shown in Fig. 1 and summarised in Table 1, encompass either single- or double-mails made with cubic, octahedral, spheric truss-like particles. As shown in Fig. 2a, In the first experiment, the beam-like in-vacuo fabrics are pinned at the two ends and excited in the middle by a shaker via a pinning jaw such that they work as pinned beams excited in bending. As shown in Fig. 2b, in the second experiment, the beam-like in-vacuo fabrics are mounted on a shaker such that they work as "flapping vibration absorbers". Table 1 summarises the principal properties of the structured fabrics analysed in this study.

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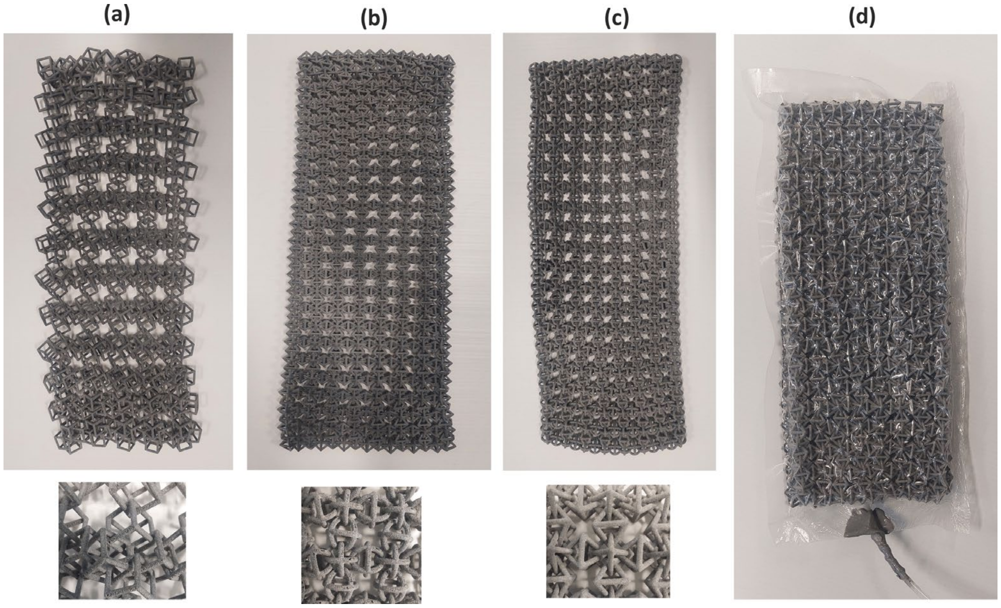
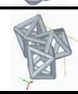
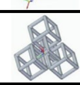


Fig. 1 structured fabrics made with (a) cubic, (b) spherical octahedral, (c) octahedral chain mails. (d) Beam specimen made by the fabric in a deflated bag.

Table 1: Prototyped structured fabrics studied in this paper with dimensions and weight

Name	**Geometry**	**Width (mm)**	**Length (mm)**	**Thickness (mm)**	**Mass (g)**
Spheres		100	210	10	49
Octahedra		110	240	15	62
Cubes		110	190	15	39

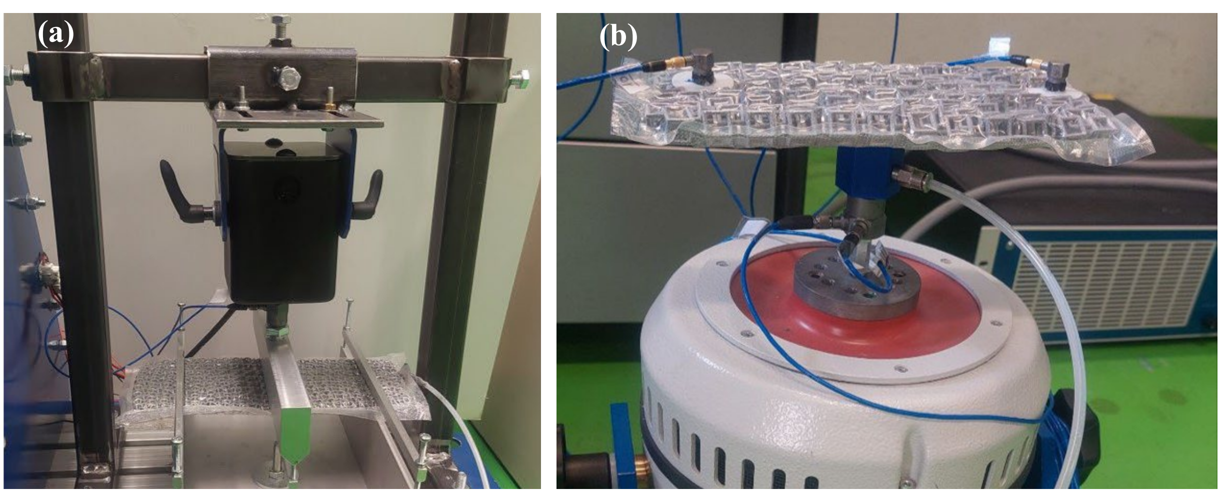


Fig. 2 (a) Six points bending machine with the tested beam specimen. (b) tuneable structured fabric vibration absorber mounted on a shaker vibration source.

Mechanical properties

Figure 3a shows the modulus and phase of the dynamic stiffness measured with the six-point bending machine with respect to the vacuum pressure in the deflated bag with the cubic structured fabric. The plot shows the typical spectrum of the middle point dynamic stiffness of a simply supported beam, which is characterised by a stiffness-like asymptotic response at low frequencies and a mass-like asymptotic response at high frequencies. At mid frequencies there is a sharp resonance through due indeed to the resonant response of the fundamental bending mode of the beam specimen. The graph shows that the vacuum shifts to higher frequencies the static bending stiffness of the material but has no effect on its apparent mass. As a result, it shifts to higher frequency the fundamental resonance too. Indeed, the graph in Figure 3b shows that, when pressure is increased from 5 kPa to 80 kPa, the resonance frequency of the specimens grows by about 20% to 25%. Also, the specimens with double layer fabrics have about 50 % to 100 % higher resonance frequency than their single layer counterparts. In general, the specimens encompassing the fabrics made with cubic grains show the highest bending stiffness and thus the highest, and widest, resonance frequency ranges. The graph in Figure 3c indicates that the loss factor of the specimens, derived with the half power bandwidth method at the first resonance frequency, are characterised by quite similar values for the three types of fabrics, which are confined between 5 % and 7 % for the single layer configuration and between 5.5 % and 9 % for the double-layer configuration.

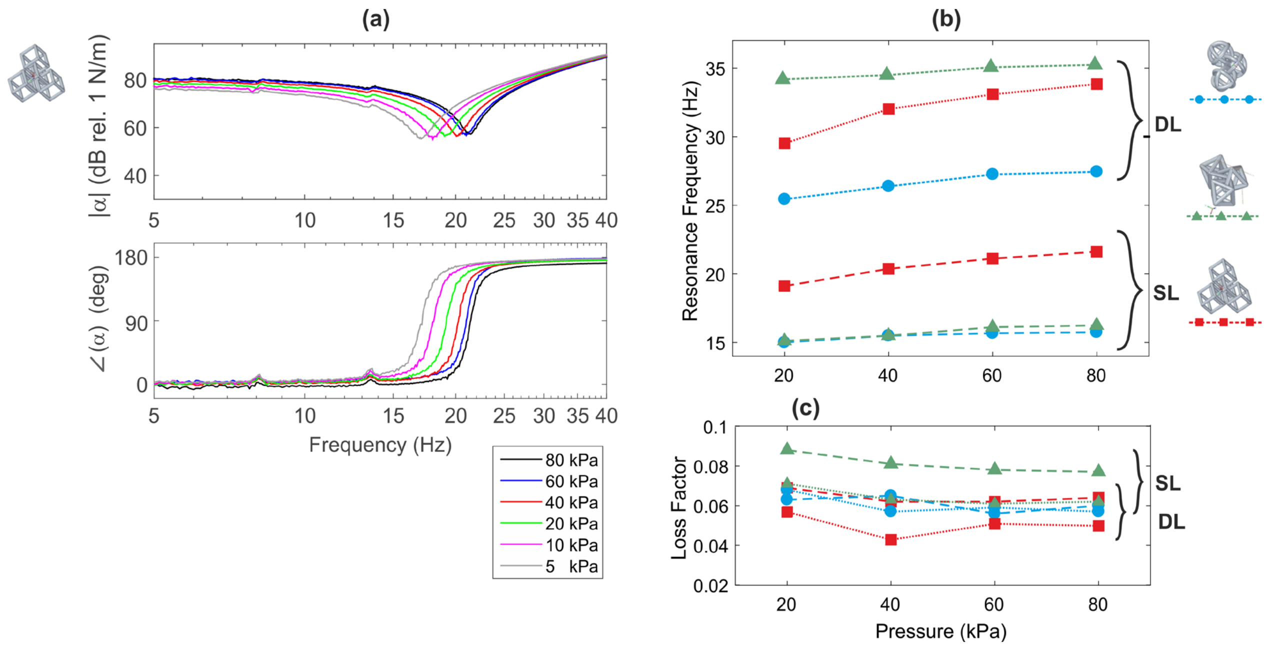


Fig. 3 Dynamic stiffness frequency response function (a) and resonance (b), loss factor (c) parameters with respect to the vacuum pressure.

Tunable Vibration Absorber

The beam specimen can be suitably used to construct a TVA. For instance, Fig. 2b shows a prototype device, which is mounted on the vibration table of a big shaker. In this case, the structured fabrics are insert in a fully sealed plastic bag, which is equipped in the middle span with a sealed inlet port built in plastic using 3D printing technology. In this way the in vacuo structured fabric acted as a two-arms beam clamped in the middle span to the inlet port, which acts as a post too. Indeed, the inlet port was designed in such a way as it served both as a connector for the vacuum tube and as a mechanical joint to fix the two-arms in-vacuo structured fabric beam to the hosting mechanical system. The vacuum was generated with an off the shelf pump and a simple circuit encompassing two valves and a vacuum gauge.

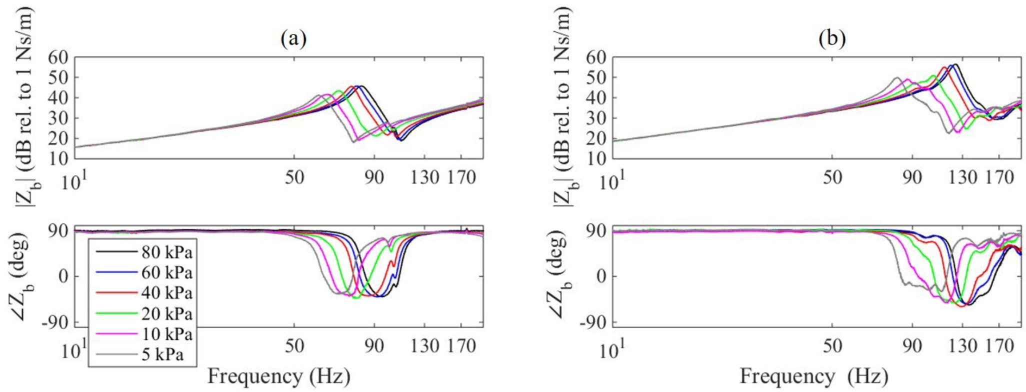


Figure 4: Impedance response for cubes assembled with one (a) or two (b) overlapped layers.

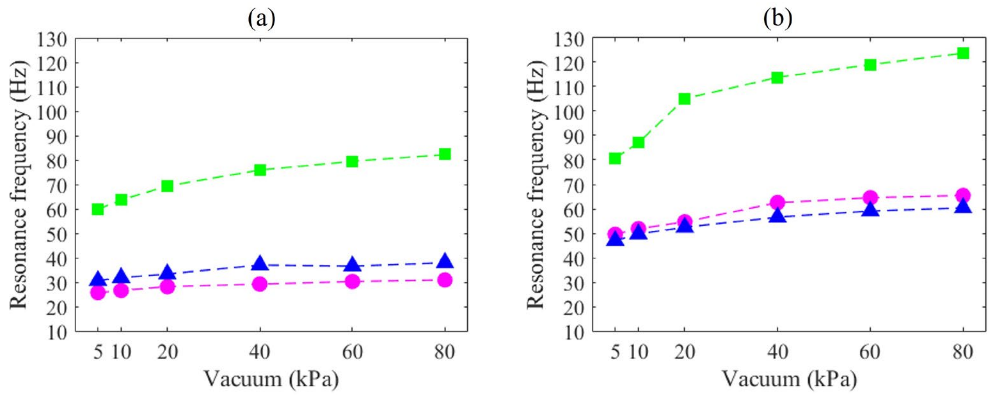


Figure 5: Measured resonance frequency of the tuneable structured fabrics assembled with one (a) or two (b) overlapped layers. Magenta for spheres, blue for octahedra and green for cubes.

Figure 4 shows the modulus and phase of the base impedance measured on the specimens encompassing either a single (left hand side plots) or a double (right hand side plots) cubic fabric vibration absorber with reference to vacuum pressure that grows from 5 kPa to 80 kPa. The spectra show the typical base impedance of a seismic mass connected to a base mass via a spring damper lumped element. Indeed, at low frequencies the spectrum is characterised by a modulus that rises proportionally to the circular frequency and a constant phase value of about $+90°$. There is then a resonance peak followed by an antiresonance through, with the phase that initially falls down to $-90°$ and then recovers to $+90°$. At higher frequencies the spectrum shows again a modulus that rises proportionally to the circular frequency and a phase that maintains the $+90°$ value. All this indicates that at low and high frequencies the device presents a mass effect. More precisely, measurements taken with the accelerometers have shown that at low frequencies the in-vacuo structured fabric beam behaves as a solid body together with the junction component, with negligible flapping effects. Therefore, the base impedance is given by the whole mass of the beam and base component. Alternatively, at higher frequencies, despite the base vibrations, the two ends of the in-vacuo structured fabric are characterised by little vibrations such that the base impedance is controlled by the mass of the base component. At resonance frequency the two ends of the in-vacuo structured fabric display large counter oscillations to the base oscillations, which generate the desired vibration absorption effect. The extent of these oscillations is controlled by the damping of the in-vacuo structured beam. Normally, to counteract harmonic vibrations, the vibration absorber is tuned in such a way as it resonates at the tonal disturbance and its damping is kept to the minimum possible value such that the hosting structure faces a large impedance load.

Alternatively, for broadband vibrations the vibration absorber is tuned in such a way it resonates at the resonance frequency of the hosting system, but in this case the damping is brought up such that the double resonant response of the combined hosting structure-TVA modes is optimally dampened.

Overall, the graphs shown in Fig. 5 indicates that the resonance frequency of the TVAs can be suitably shifted to higher/lower values by increasing/lowering the level of vacuum in the bags. For the 5 to 80 kPa pressure range, the single layer TVAs are characterised by resonance frequencies comprised between 60-85 Hz (cube grains), 25-30 Hz (sphere grains), 30-40 Hz (octahedra grins). Alternatively, the double layer TVAs are characterised by resonance frequencies comprised between 80-125 Hz (cube grains), 50-65 Hz (sphere grains), 45-60 Hz (octahedra grains). This confirms that the resonance frequency of the TVAs can be suitably tuned over significant ranges by varying the vacuum pressure. Moreover, these ranges can be further enlarged by adopting multiple layers with combinations of different grains.

Summary

The experiments presented in this paper have shown that the bending stiffness of the in vacuo structured fabric beams can be suitably varied by changing the vacuum pressure in the bag. This effect depends on the type of elementary truss grains of the fabric and on the number of layers wrapped in the bag. For instance, the cubic and octahedral fabrics offers the highest bending stiffness respectively for the single- and double-layer configurations. When the vacuum pressure is raised from 5 to 80 kPa, the stiffness of two-layers cubic fabric beam is doubled. Also, the double layer octahedral structured fabric shows 5 times higher stiffness than the single layer one. These properties can be suitably employed to shift the resonance frequency of the fundamental flapping flexural mode when the in vacuo structured fabric is operated as a vibration absorber. For instance, the study has shown that, for 5 to 80 kPa pressure range, the resonance frequency of either the single- or double-layer vibration absorbers can be increased by 30% to 40%. Also, the resonance frequency of the double layer vibration absorbers is about 50% higher than that of the single layer absorber.

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