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VIBRATION RESPONSE OF TUNEABLE STRUCTURED FABRICS: MODELLING, IDENTIFICATION AND TVA IMPLEMENTATION

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ABSTRACT

This paper is focussed on a new material made by interwoven rigid elements that form flexible garments such for example chain mail armours. These structures are fabricated with different geometries (octahedral spheres, octahedra, cubes) using 3D-printing technology. The material is wrapped in a bag whose vacuum pressure is tuned with a pump system such that the stiffness and damping properties of the resultant smart structure can be suitably tuned. To start with, the paper presents dynamic 6-point bending tests on the mechanical properties of a few vacuum structured fabric samples. The tests show that the bending stiffness and fundamental resonance frequency of the specimens can be increased significantly by augmenting the vacuum in the bags. The damping effect does not depend substantially on the vacuum level but varies significantly with respect to the geometry of the constitutive elements of the fabrics. Finally, the paper shows that this smart structure can be conveniently used to develop a Tuneable Vibration Absorber, which can be used to control either the time-harmonic response of a mechanical system subject to variable tonal excitation or the broad-band resonant response of a structure whose dynamic properties may vary over time.

Keywords: *structured fabrics, 3D printing, vibration absorber, smart material.*

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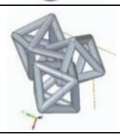
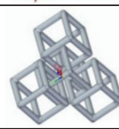
1. INTRODUCTION

The past two decades have seen a growing interest on Tuneable Vibration Absorbers (TVA) [1], which can be tuned while in operation to effectively control the harmonic response of mechanical systems subject to time-varying tonal excitations. They exploit smart materials such as shape memory alloys [2], electrorheological and magnetorheological elastomers [3], and piezoelectric patch/stack materials connected to electrical shunts [4]. The stiffness of these systems can be controlled electrically so that the fundamental resonance frequency of the absorber can track the frequency of the tonal excitation. Normally, to control tonal vibrations the damping should be set to rather low values [5].
This paper studies a new smart material, the Tuneable Structured Fabric (TSF) [6], and investigates its use for the design of a novel TVA, which is composed by a strip of a structured fabric wrapped in a vacuum bag whose middle span is clamped to the post of the absorber [7]. The bending stiffness and mechanical loss properties of the beam can then be corrected by varying the vacuum pressure in the bag. Hence, the fundamental resonance frequency and the damping factor of the in-vacuo structured fabric vibration absorber can be tuned online in such a way as to track the frequency of a tonal excitation.

2. IN VACUO STRUCTURED FABRICS MODELLING

In general, structured fabrics are composed by a network of rigid elements linked together in such a way as to form an interwoven material. A classic example of this material is given by armour chain mails worn in the middle age by knights and soldiers. In this study, the structured fabric is wrapped in a sealed plastic bag. As happens for food packaging, e.g. rice or coffee bags, if the pressure in the bag is progressively reduced, the material becomes more and more stiff. This is due to jamming between the elements of the interwoven structure. Jamming is a phase transition from a fluid to a solid state that depends both on compression and shear stress. The prototypes designed and built for this study, uses structured fabrics made in Nylon PA12 material by 3D printing technology. The structured fabrics built for this study have been modelled in SolidEdge software and then produced with an HP Multi Jet Fusion printer. The fabrics were designed either with single or double strips such that they resembled a thin and wide beam structure. The airtight bag was home-made starting from off the shelf bags for food packaging. Also, a 3D printed inlet port was built in plastic using 3D printing technology and sealed to the middle span of the plastic bag. The vacuum was generated with an off the shelf pump and a simple circuit encompassing two valves and a vacuum gauge. Table 1 provides the geometries and principal dimension of the three truss-like particles considered in this study.

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

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

3. SIX-POINT BENDING TESTS

The static and dynamic bending stiffness of the two-arms in-vacuo structured fabric beam were measured with the 6-points bending setup depicted in Figure 1, so that the beam undergoes full positive-negative bending cycle. This work

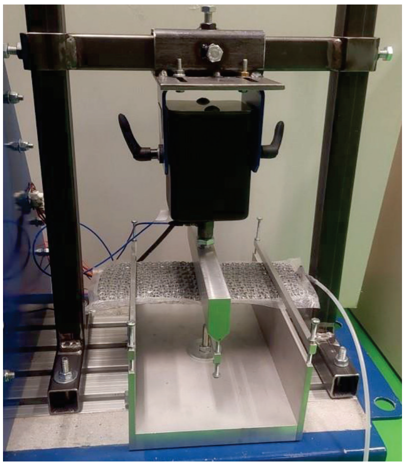


Figure 1. Testing setup for the dynamic material characterization by six-points bending test.

is focussed on the dynamic characteristics of TSF. Hence the dynamic stiffness FRFs were measured in a frequency range comprised between 5 and 40 Hz. Two test sets were carried out encompassing either a single or a double layer of each structured fabric. The tests were run with the following levels of confining vacuum pressures: 80 kPa, 60 kPa, 40 kPa, 20 kPa, 10 kPa and 5 kPa.

As summarised in Figure 2, the bending stiffness of the in-vacuo structured fabrics increases as the vacuum level in the bags is raised. Consequently, the resonance frequency tends to raise as the level of vacuum in the bags is increased. The double layer configurations offer comparatively higher bending stiffnesses, and thus larger resonance frequencies, than the single layer configurations. For the single layer configuration, the cubic fabric presents the highest bending stiffness; in contrast, for a double layer configuration, the octahedral fabric offers the most rigid structure. The fabric made with cubes is characterised by the largest range of stiffnesses, and thus of resonance frequencies.

To better investigate the damping, displacement-velocity diagrams were recorded for time-harmonic excitations. The phase diagrams showed closed loop curves, which confirm the presence of hysteresis. In general, the loops resembled extended elliptic curves indicating a linear material damping effect. According to the literature [8], a Voight damping model given by a damper in parallel with a spring was employed. As a result, the material loss factor value was calculated. Figure 3 shows the loss factors derived from measured hysteresis loops for the three types of single- and double-layer fabrics with respect to different level of vacuum pressure. The graphs confirm indeed a nontrivial loss factor effect, which interestingly maintains quite a constant value comprised between 5% and 7% with respect to the type of grain, the number of layers and the vacuum pressure.

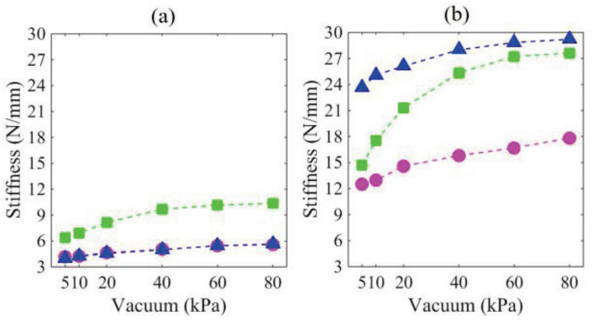


Figure 2. Stiffness of the tuneable structured fabrics assembled with one (a) or two (b) overlapped layers. The points represent the measured data. Sphere-grains (magenta), octahedra grains (blue) cube-grains (green).

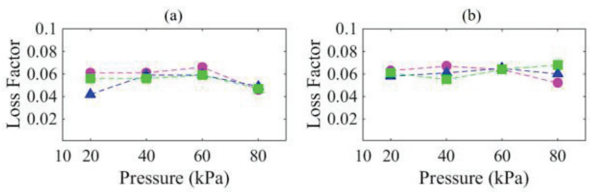


Figure 3. Structural loss factor of the tuneable structured fabrics assembled with one (a) or two (b) overlapped layers. The points represent the measured data. Magenta for spheres, blue for octahedra and green for cubes.

4. TUNABLE VIBRATION ABSORBER DESIGN AND CHARACTERISATION

The in-vacuo structured fabric beam can be used as a TVA device. The TSF absorber has been designed as a free-free beam clamped in its midspan. To characterise the vibration absorption properties of the TVA system, base impedance FRF measurements were taken with the setup shown in Figure 4. The measurement system is composed by a large shaker whose vibrating platform was instrumented with an impedance head. For illustrative purposes, Figure 5 shows the modulus and phase of the base impedance, measured on the in-vacuo beams encompassing either a single (left hand side plots) or a double (right hand side plots) layer of cube structured fabrics. Each plot shows six curves obtained for the six confining vacuum pressures reported above. The spectra show the typical base impedance of a seismic mass connected to a base mass via a spring in parallel with a dashpot.

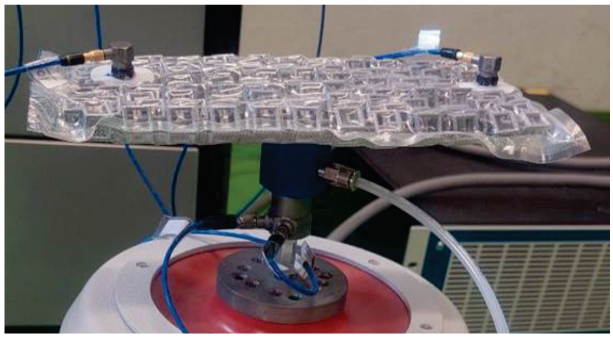


Figure 4. TVA test set up.

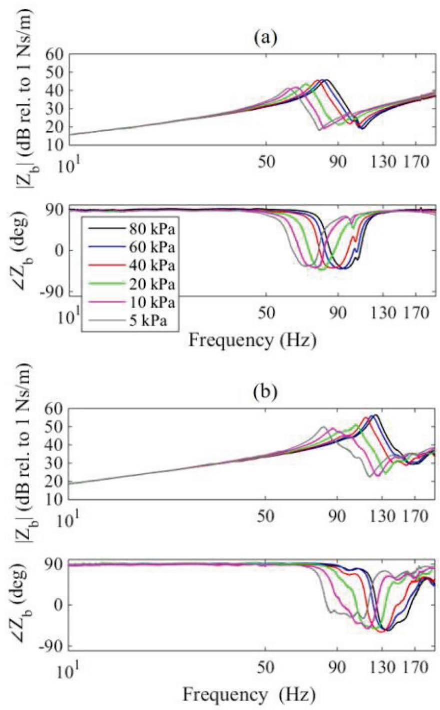


Figure 5. Impedance response for cubes assembled with one (a) or two (b) overlapped layers.

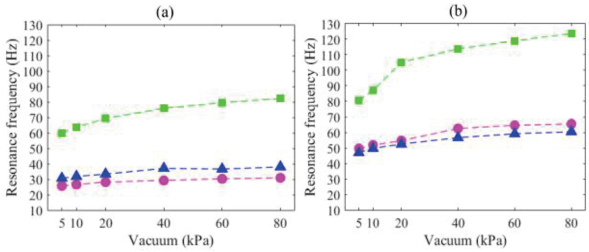


Figure 6. Measured resonance frequency of the tuneable structured fabrics assembled with one (a) or two (b) overlapped layers. Magenta for spheres, blue for octahedra and green for cubes.

The plots in Figure 6 indicate 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 (octahedral sphere grains), 30-40 Hz (octahedra grains). Alternatively, the double layer TVAs are characterised by resonance frequencies comprised between 80-125 Hz (cube grains), 50-65 Hz (octahedral 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.

5. CONCLUSIONS

This paper has investigated a new smart material, the TSF, obtained by creating and controlling a variable vacuum pressure around a structured fabric. The results of this experimental study show that each type of fabric is characterised by neighbouring but separate ranges of stiffness such that a rather large range of stiffnesses could be generated with beams encompassing multiple layers made from different types of elementary grains. In general, if higher ranges of stiffness were required, it would be better to use cubic double layer structures. Instead for lower stiffness ranges, it would be preferable to use spherical or octahedral structured fabrics.

Moreover, the vibration response of a TSF-TVA has been investigated. The paper shows that the bending stiffness of the in vacuo structured fabric beam 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. The study has shown that, for the 5 to 80 kPa pressure range, the resonance frequency of either the single or double layer TVA can be increased by 30% to 40%. Also, the resonance frequency of the double layer TVA is about 50% higher than that of the single layer TVA. This suggests that rather wide tuning ranges can be achieved with designs encompassing multiple layers and different types of elementary truss grains. The study has also shown that the beam is characterised by low damping, with a structural loss factor that does not change significantly with the level of vacuum in the bag as well as with respect to the number of layers and the type of elementary grains.

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