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Enhanced acoustic insulation properties of composite metamaterials having embedded negative stiffness inclusions

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ABSTRACT

Despite the fact that the concept of incorporating Negative Stiffness (NS) elements within mechanical systems was formulated and validated more than 40 years ago, it has only recently received consistent attention. In this work, the design of a layered mechanical metamaterial having implemented NS inclusions is presented and its acoustic wave propagation properties are modelled. A dedicated two-dimensional periodic structure theory scheme is developed in order to compute the frequency dependent damping loss factor of the metamaterial structure. The acoustic transmission properties through the modelled panel are computed within a Statistical Energy Analysis (SEA) scheme. It is demonstrated that the suggested layered metamaterial exhibits highly superior acoustic insulation performance close and above the acoustic coincidence range, thanks to the drastic increase of its structural damping properties implied by the NS elements. Additionally, the proposed configuration presents superior performance in a broadband frequency range when compared to a viscoelastic damping constraint layer of equivalent mass.

1. Introduction

The need for low-cost and low-mass vibration isolation within the modern aerospace, automotive and energy industries has recently motivated research groups at a worldwide level to develop a number of novel vibration isolation concepts. Moreover, the use of composite layered materials in the transport industry is becoming more important due to the need for designing and manufacturing lightweight, energy efficient products. Despite their superior structural characteristics, composite structures exhibit inferior dynamic and acoustic performance levels compared to conventional metallic ones. The large number and variety of elastic waves propagating within a layered composite, implies high structure-borne vibration transmissibility and high noise transmission. Structural integrity as well as passenger comfort can be compromised by high levels of vibration and noise transmitted through industrial structures. Widely employed damping enhancement methodologies nowadays include the addition of viscoelastic material layers that are expensive in terms of additional, non-structural mass and space usage. Moreover, it is also noted that whilst viscoelastics have shown potential for increasing attenuation in the high frequency domain, there is currently no recognised passive design configuration for efficiently damping low frequency vibration (that is the first 5–10 structural modes). Research interest has therefore focused towards achieving increased structural damping through measures of reduced mass, volume and cost impact. A methodology receiving increasing attention due to its attenuation efficiency (particularly in the low-frequency range) is the inclusion of internal tuned resonators [1]. As demonstrated below, a number of authors has suggested that the inclusion of negative stiffness elements in the structural ensemble, can drastically amplify internal oscillations and consequently the structural damping performance of the configuration.

The beneficial impact of NS mechanisms on vibration isolation has been reported as early as 1957 in the pioneering publication of Molyneaux [2]. It was followed by the milestone developments of the authors in [3,4] where the design of mechanical isolating NS mechanisms was achieved through the use of discrete macroscopic elements. It was demonstrated that the exceptional performance of these systems was attained through reducing the strain energy stored within the system during oscillation (by reduction of the overall effective stiffness), thus increasing the loss factor of the

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oscillator defined as:

$$\eta = \frac{\text{energy dissipated per cycle}}{\text{maximum strain energy stored in the system}}. \quad (1)$$

There exist generally two design streams of NS inspired structures; one of them focusing on the development of continuous metamaterials containing NS phase inclusions (see [5]) and the second one dedicated to the design of systems containing discrete macroscopic NS elements. Both research streams share common reported benefits (high structural damping and vibration isolation performance levels) however not the same challenges. With regard to the design of macroscopic NS elements, a variety of designs has been proposed for the realisation of such configurations, incorporating various structural elements such as post-buckled beams, plates, shells and precompressed springs, arranged in appropriate geometrical configurations [6–11]. Experimental validation of NS vibration isolation mechanisms with their designs based on Euler post-buckled beams have been presented in [12–16]. In automotive engineering, applications include the design of NS suspensions [17,18] as well as vibration isolation seats [19–21] for improved passenger comfort. A high-speed railroad vibration isolation system employing NS elements was discussed in [22]. The authors in [23–26], employed structural NS elements at the basis of civil structures in order to suppress vibration without large force transmission to the superstructure during extreme earthquake excitations.

Multiphysics NS mechanisms incorporating magnetic and magnetorheological fluid elements have been proposed, however the additional mass required by such designs prohibits their application in moving structures. In [27–29] a NS magnetic spring mechanism exhibited high vibration isolation performance levels. In [30,31] the authors suggested magnetorheological adjustable NS devices with enhanced vibration isolation properties. In [32] the design principles and experimental validation of magnetic NS dampers were presented, comprising several permanent magnets in a conductive pipe.

In this paper the authors propose the design of a novel layered mechanical metamaterial having implemented NS inclusions. The design and tailoring of the mechanical characteristics of the internal NS inclusions is initially discussed. A two-dimensional periodic structure theory scheme is employed and modified in order to derive a dedicated expression for the damping loss factor of the structure as a function of the elastic waves propagating within it. The acoustic transmission properties through the modelled panel are computed within a statistical energy analysis scheme. The numerical results provide evidence of a drastic increase of the damping loss factor as well as of the acoustic isolation performance of the proposed NS layered metamaterial in a broadband frequency range.

The paper is organised as follows: In Section 2 the design of the mechanical NS inclusions is discussed and a number of numerical parametric results are provided on a variety of NS designs. In Section 3 a periodic layered structure having NS inclusions is Finite Element (FE) modelled. The characteristics of the elastic waves propagating within the structure are sought through a two-dimensional periodic structure theory scheme. The damping loss factor associated with each propagating wave type is computed, as is the sound Transmission Loss (TL) of the structural panel. Conclusions on the exhibited work are eventually drawn in Section 4.

2. Design of mechanical NS internal inclusions

In this work, the authors are interested in implementing macroscopic NS elements with mechanical characteristics specifically tailored for maximising the damping properties of the considered

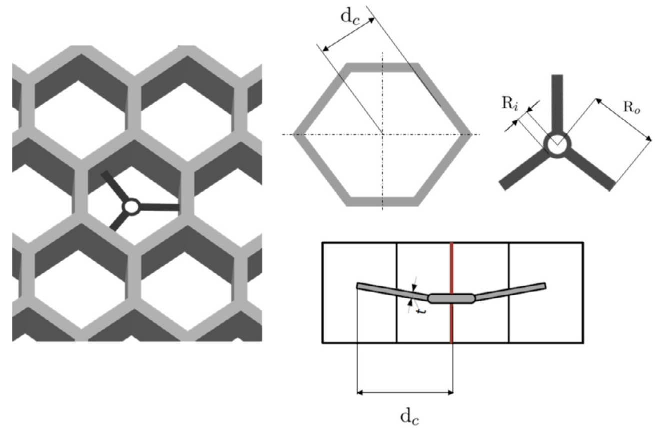

Fig. 1. Illustration of the proposed tripod mechanism: Left: View of the employed prestressed NS elements within the honeycomb architecture of the core structure. Right: Side view of the NS elements within a honeycomb cell. Positive stiffness elements and honeycomb cell are also illustrated.

layered composite structure. As weight is a design factor of principal importance, configurations of a purely mechanical nature will be preferred. The majority of mechanical NS designs proposed by researchers nowadays are generally related to Euler beams operating in their post-buckling regime. Such structures are straightforward to manufacture and incorporate, however in the case of being implemented within the honeycomb core of a layered structure they could induce highly asymmetric stress loading conditions within the structural core, leading to possible fatigue and failure.

In this work, an element that is more stable and suitable for implementation in honeycomb cores is proposed as illustrated in Fig. 1. Similar to a beam, the proposed tripod structure snaps through around the equilibrium point during operation, rendering it effectively a NS element around that region. Positive stiffness (viscoelastic straps) are attached to the element in order to render the ensemble of the inclusion stable, and facilitate its activation during operation.

A parametric survey is hereby performed in order to determine the sensitivity of the NS characteristics of the proposed structure as a function of its design. For this reason, the inclusion is FE modelled as illustrated in Fig. 2 and nonlinear quasi-static solutions are sought in order to determine its mechanical characteristics within the operational displacement regime. The stress distribution on the honeycomb cell was tested as shown in Fig. 3 and proved to be satisfactory. More specifically, using technical characteristics of honeycomb that is commercially available, the FE analysis showed that the stresses that were applied on the honeycomb cell during the snapping movement of the tripod mechanism did not exceed the 10% of the material's strength. The design characteristics under investigation are the ratio of the mechanism's outer and inner dimensions $r_R = R_o/R_i$, the thickness t as well as the prestress factor equal to the ratio of the outer dimension of the mechanism R_o and the actual size of the honeycomb cell d_c expressed as $p_f = R_o/d_c$. A two-step, nonlinear quasi-static analysis is performed. The structure is initially prestressed to the position corresponding to it being fitted inside the honeycomb cell. A small perturbation load is applied in order to facilitate the convergence of the FE solution close to the bifurcation point of the analysis (i.e. ensure a stable deflection of the tripod structure upwards during precompression). The second step consists in applying displacement constraints at the central ring of the tripod in order to trigger the snap-through process. The reaction forces measured at the supports are exhibited below.

The general trend for the displacement/force characteristics of the snap-through region of the proposed configuration are shown in Fig. 4. It is observed that a lower r_R factor will not only imply