Low-Frequency Broadband Vibration Dampers from Nonlinear Structures with Metamaterial Properties

SG Demiryurek The University of Sheffield, Sheffield, United Kingdom

A Krynkin The University of Sheffield, Sheffield, United Kingdom

1 ABSTRACT

Particle dampers are used to treat structural vibration for more than a decade. Kinetic energy and momentum changes in the contact interactions are the main reasons for energy dissipation in particle dampers. Their effectivity depends on many parameters including particle contact and particle geometry making the particle damping application nonlinear. This research is focused on the application of particle dampers arranged in a periodic array to form metamaterial and is aimed at broadening the low-frequency range vibration dissipation. Metamaterials are usually made of an array of resonators forming subwavelength structures that offer superior vibro-acoustic properties. The enclosure cavity of the particle dampers is designed to have local resonance properties within the selected mode frequencies of the main structure that is under excitation impact. Equivalent structure continuum modelling of the particle dampers has been accomplished through DEM and the analytical methodology using granular structure contact properties. The metamaterial unit cell modelling is based on the Bloch-Floquet conditions simulated with COMSOL Multiphysics using FEM solver. The performance of the proposed metamaterial design is validated with the finite beam model which is treated with an array of particle dampers. The obtained results illustrate that implication of the periodically arranged particle dampers in metamaterial formation exhibit promising dispersion properties and vibration attenuation.

Keywords: Metamaterial, Nonlinear Damping, Passive Damping, Particle Damping, Structural Vibration, Nonlinearity, Vibro-acoustics

2 INTRODUCTION

Particle damper is a novel type of passive damping varieties which constitutes multiple granular structures in an enclosed geometry. These granular structures can be made of metals, ceramic, or polymer. In addition to that, the geometry of the granules might be in any shape, but they are mostly preferred as spherical shaped structures. The material of the granular structures has several options from metals, polymers, and ceramics. There are varieties of particle dampers according to their enclosing cavity geometry, number of particles placed in a single cavity, the number of cavities, etc [1].

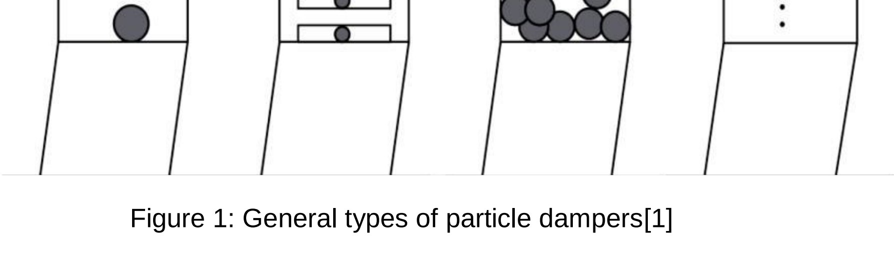

Figure 1: General types of particle dampers[1]

Energy is dissipated through the kinetic energy and momentum changes between the damper elements which are granular structures and enclosing cavity walls. Contact interactions, which is mainly inelastic collision between the granules and between the granules-the walls drive the energy level changes. Even though the energy is dissipated through the contact properties between the damper parts, the dissipation is sensitive to the change in the frequency and the amplitude levels. This specific detail on the energy dissipation of the particle damper is referred to as the amplitude dependency or nonlinearity of the particle dampers [2].

Figure 2 shows the mechanics of the kinetic energy dissipation and the momentum changes. Depending on the material properties and the size of the colliding particles, kinetic energy level is changed after the collision. In addition to this, the velocity of the particles might be changes; hence, their momentum levels are also changed. Thus, the physical property changes between these colliding structures are the main reason of the particle dampers [3], [4].

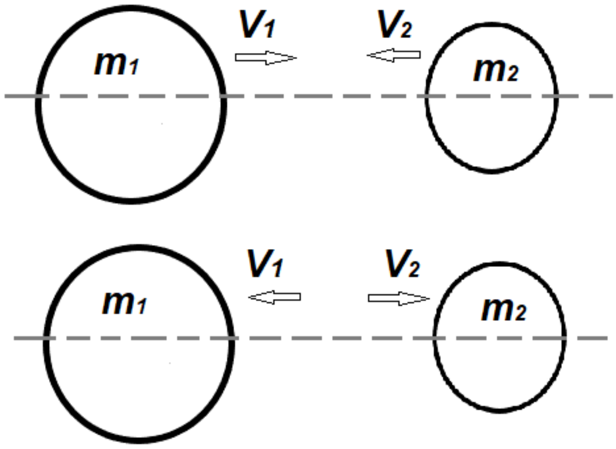

Figure 2: Colliding two particles

Energy dissipation of the particle damper have been attempted by several researchers using experimental, numerical, and analytical methods. Experimental methods have helped to evaluate the properties and develop real applications. This methodology increases the understanding outcomes of the analytical and the numerical analysis. However, there are many parameters to be considered in the experimental options which makes the work complicated. Whereas the analytical methods are inclusive of those several parameters, such as contact details between the granules and the physical properties. Taking each parameter into account require great attention and this work gets more and more complicated while each parameter participates. Therefore, this option is less applicable and much more complicated in order to gain information from the damping. Lastly, the numerical methods are inclusive of many parameters that can be attached for the particle damping research. Even though the numerical methods are computationally expensive, these options are quite applicable when they are used systematically. This means that the research might easily reach to some beneficial information levels about the damping properties of the particle dampers.

According to the periodically arranged locally resonant structure studies, this arrangement gives opportunity to the structures to dissipate the undesired energy and tune the structures. This application has similar impacts as in the damping applications; however, using these applications in an array increase the beneficial applicability. For instance, acoustic metamaterials with homogeneous material properties (using in subunits) might give stop band effect where there is no dissipation or subwavelength waveguide opportunities [5], [6].

In this research, granular structure-based passive dampers are aimed to be used in a periodic array in order to form a metamaterial which would give opportunity to tune low frequency range vibration dissipation. Metamaterials are usually prepared using array of resonators forming subwavelength structures that offer superior vibro-acoustic properties. The cavity of the particle dampers is designed to exhibit locally resonant structure properties tuned to match the selected mode frequencies of the main structure that is under excitation impact. Equivalent structure continuum modelling of the particle dampers has been developed through DEM and the analytical methodology using granular structure contact properties. The unit cell modelling for the metamaterial is based on the Bloch-Floquet conditions simulated within COMSOL Multiphysics using FEM solver. The performance of the proposed metamaterial design is validated with the finite beam model. The results show that implication of the periodically arranged particle dampers in metamaterial formation exhibit promising dispersion properties and vibration attenuation.

3 METHODOLOGY

This study based on numerical methods involving multiple physics modelling. In particular, the attempt is made to couple particle contact mechanics and individual damper response to the excitation with metamaterial theory.

To validate the numerical models and results, experimental analysis in this study is designed using a fixed-fixed end conditioned beam, a shaker and locally resonant structure as a damper. The granular structures are in 1/16 inches size steel particles which were used in 1.675% filling level. However, there are several more filling level experimental study results have been attached in the results section for an individual particle damper performance.

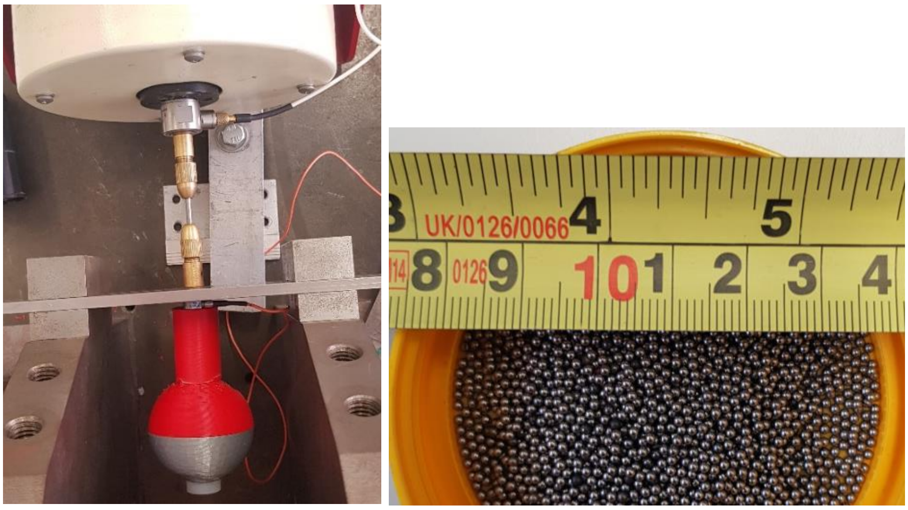

Figure 3: Two sphere in contact

Discrete Element Method (DEM) has been used in order to define and analyse the contact relations between the granular structures. This method has also been used to define continuum structure in Finite Element Modelling (FEM) which corresponds to the pack of granular structures. Hertz Mindlin Contact Theory has been applied to the contact between the particles and particle-wall relations. This contact modelling raises opportunity to analyse the tangential and the normal directions of contact forces at the contact interface. Depending on the filling fraction and material properties of the contact elements, the analysis of applied the sinusoidal excitation on the damper cavity-particles system informs about the number of contact and the hydrostatic pressure of the enclosing cavity. The material properties of the equivalent structure replacing the pack of particles could be calculated analytically.

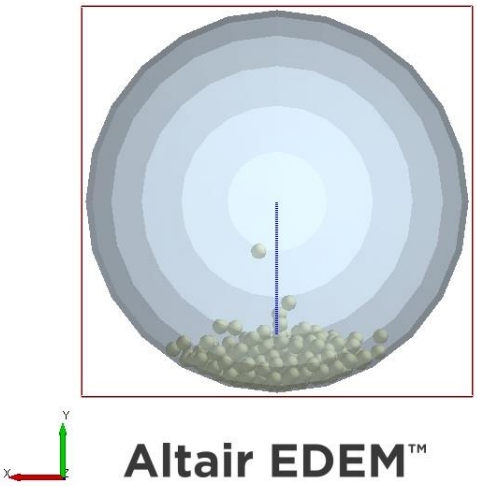

Figure 4: DEM used modelled geometry of cavity and particles

Applying the new material properties for the continuum structure modelling in Finite Element Method is a straightforward methodology. The enclosure cavity and the continuum structure for the pack of granules are geometrically modelled and the material properties are defined either from the previously defined materials or from the blank material options in COMSOL Multiphysics. Finite structure analysis in frequency domain is modelled using a base structure which is a beam as in the Figure 5.

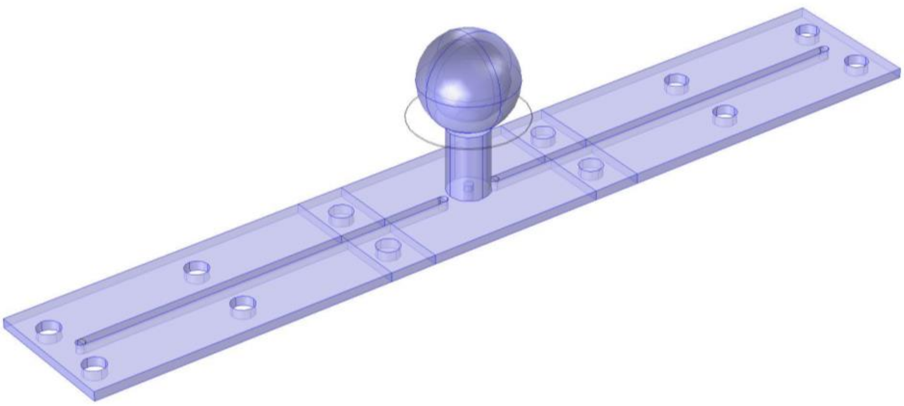

Figure 5: FEM used beam and damper system

In addition to the finite structure modelling and analysis, Bloch-Floquet method has been applied to the mass-spring modelling system to investigate the effect of the local resonances on the performance of metamaterial. Mass-spring system modelling is a simplistic option to model a complex non-dispersive metamaterial modelling which could be used to approximate damper-metamaterial in infinite structure modelling. Figure 6 shows the design of the mass-spring modelling of the beam-damper-particle attachment. Each layer has additional mass-spring definition in the modelling.

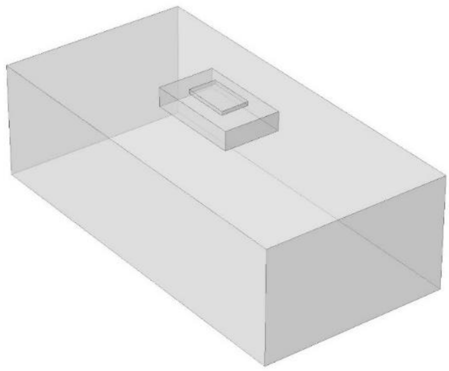

Figure 6: FEM used mass-spring modelling

In order to model the infinite periodic structure, the Bloch-Floquet conditions, are applied to the surface in the direction of the beam main axis as shown in Figure 6. Material properties, spring constants and damping constants are applied according to the resonator damper container properties and experimental-DEM study results.

4 RESULTS

According to the experimentally studied damper-shaker tests, multiple damper arrangement on the main structure helps to tune the modes in the given frequency range as shown in Figure 7. Increasing the particle amount in the damper cavity, in other words increasing the filling ratio, has helped to change the frequency response from the beam since the particles interact with each other progressively while increasing the amount of the particles.

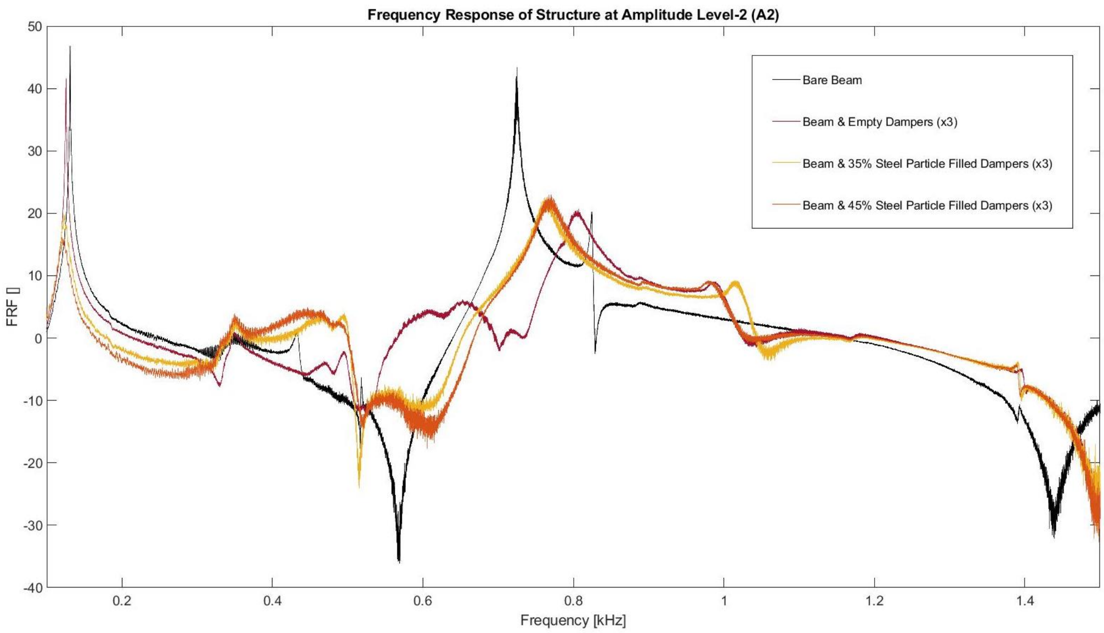

Figure 7: Experimental results of the damper arrangement

Experimental study data from the bare beam is used to model EDEM numerical analysis. Excitation properties were calculated using the analytical expressions of the displacement values through the force-acceleration data of the experiments. Specifically selected filling level of 1.675% filling ratio has been applied in the EDEM numerical analysis and equivalent material properties has been calculated using the methodology which was explained in the earlier articles [7]. FEM-based finite and infinite structure modelling have been prepared using the beam, resonating container and equivalent material properties as explained in the methodology.

According to the infinite structure modelling using the unit cell modelling in the lights of Bloch-Floquet Theory, there are two modes on the bare beam which are optical and acoustical modes, given in Figure 8. In addition to that, adding resonating container properties to the bare beam (Figure 9) in the unit cell modelling shape the dispersion properties as showing the eigenfrequencies and band properties. Adding particles to the container has helped tuning the eigenfrequency of the beam-damper mechanism and increase the stop band opportunities.

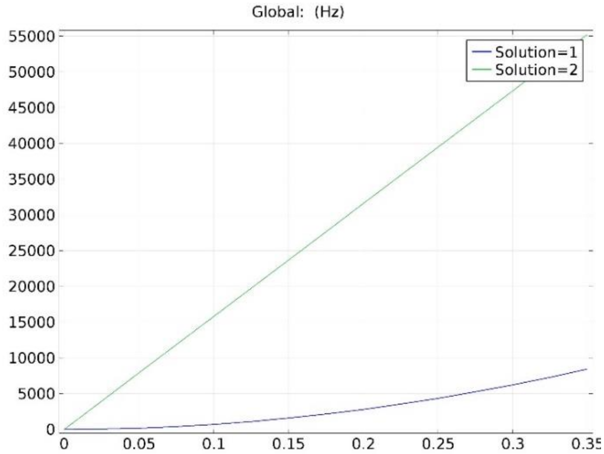

Figure 8: Dispersion figure of bare beam

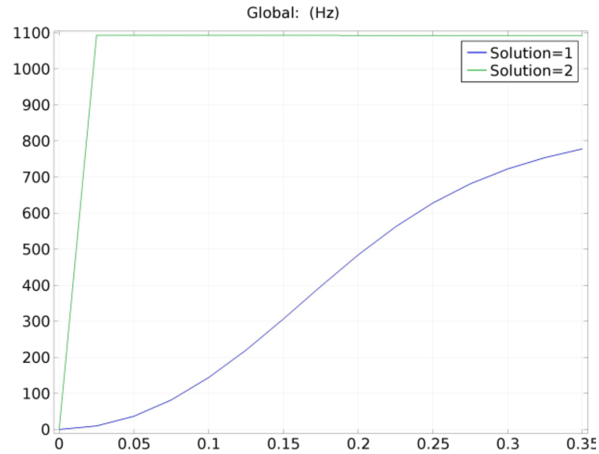

Figure 9: Dispersion figure of bare beam-empty container

This research is developed with an idea of using particle dampers I an array of arrangement while showing locally resonant properties. As stated in the experimental and numerical study results, particle dampers are useful and applicable passive damping options. In addition to that, locally resonant properties on the damper casing and particles increase the opportunity to tune the main structure in the resonating frequency levels. This idea has been proven in the unit cell modelling analysis using Bloch-Floquet Theory. The nonlinearity of the granular structure-based passive damping might be tuned and controlled in this way which the resonating damper cavity properties. The further research idea is planned to work on increased filling level of particle dampers and changing the unit cell properties while developed damping properties in the modelling.

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