

Non-linear Metamaterial Structures: Array of Particle Dampers

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ABSTRACT

Passive dampers to treat the excessive structural vibration has long been researched and used in industry. Multiple particles placed in a container can be used to dissipate excessive vibration through the inelastic collisions between particles and cavity of the damper has been shown. However, their application is usually limited to treating certain modes of structural vibration and their performance is highly dependent on location. Another limitation of the particle dampers is nonlinear character caused by discontinuity and randomness of the collisions and velocity of the particles. In this paper, it is proposed to modify a particle damper into a metamaterial type structure in order to expand the applicability range. Metamaterials are known to exhibit subwavelength performance offering superior vibro-acoustic properties over a wide range of frequencies. To maintain metamaterial properties, the casing of the particle damper is designed to resonate near selected modal frequencies. The Bloch-Floquet Theory is applied in studying the singly periodic arrangement of the resonating damper shells with and without particles. Finally, the nonlinear effects observed in the metamaterial structure made of particle dampers are modelled numerically to predict their vibro-acoustic effects in finite structures. The theoretical, numerical predictions are compared with the experimental results. Keywords: Metamaterial, Nonlinear Damping, Passive Damping, Structural Vibration, Nonlinearity

1. INTRODUCTION

Mechanical oscillations in the systems causes undesired vibrational problems which needs to be solved with damping options [1]. Passive damping methods, which are able to be used in the certain frequency ranges, do not require external energy to be effective on the structural vibration. Examples of the passive dampers and their applications are explained in [2], [3], [4], [5]. Their problem is to be sensitive to the temperatures, or wear with usage, or leakage as depending on the application type. Efforts were put on finding a better solution to the structural vibration. Impact damper is one type of passive dampers known as acceleration damper [3] which was invented after the evaluation of the weaknesses and the problems on some of the passive dampers. It is made of one structure consisting a cavity which is either inside the primary (main) structure or externally attached to the main structure. Single particle is placed in the cavity, moves there and collides with the walls. Energy dissipation mechanism comes from its colloidal behaviour with the cavity wall under dynamic load [4]. In order to increase the effects of impact damper, the damper is modelled with more than one cavity to place single particle inside; it is called as ‘Multi-unit impact damper’. Impact damper was found less sensitive to the system properties such as temperature level and excitation conditions which

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are the advantages of its usage; however, they were found noisy. In order to overcome this problem, the idea was to place more than one particle in the same cavity which have the equal mass of the single particle. The new arrangement was called as ‘Particle damper, PD’. Concerning to increase the performance, PD is designed to consist several cavities for the multiple particles, known as ‘Multi-unit particle damper’. Figure 1.1 shows these varieties of the particle dampers [1]. PD, which is capable to work under rough conditions, is improved to be effectively used in the wider range of frequencies and needed less maintenance [6].

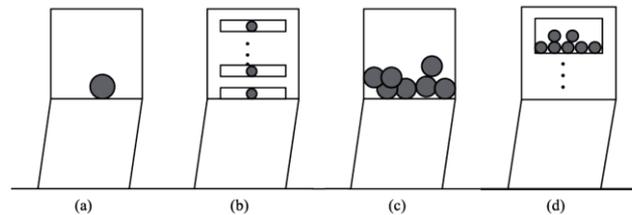


Figure 1.1: (a) Impact Damper, (b) Multi-unit Impact Damper, (c) Particle Damper and (d) Multi-unit Particle Damper

Damping properties of the particle damper were defined as a combination of friction, elastic and plastic collision losses with momentum changes. The particles move in the cavity, and their movement depends on the level of dynamic excitation. There are two types of collisions for this case: particle/particle collisions and particle/cavity wall collisions. The dissipation of energy and momentum changes through the vibratory structure are accomplished by the collisions, frictional effects, deformations and loss mechanisms [7]. In order to define working parameters and to find a better damper characteristics experimental methods were followed, mainly [8]. Experimental studies showed that PD has limited applications to treat the number of modes in the structural vibration. Additional to this limitation, discontinuity and randomness of the particle collisions cause nonlinearity on the particle dampers. This undesired situation was related to the frictional effects of collisions in the loss mechanism. Furthermore, PD performance varies with the size of the particle, volume of the cavity, packing ratio, direction of the excitation, material properties of the particles, etc. Although, PD is effective reducing the structural vibration, highly nonlinear characteristics are undesired. Therefore, efforts are on finding more effective PD design criteria with several approaches.

Metamaterial phenomena are another effective dispersive mechanism and another topic of this research as an approach for PD studies. Metamaterial is designed as subwavelength structure and can perform to control the wave bigger than the characterised structural size [9]. This engineered structure is modelled to show local resonance effects on the main structure under vibratory process [10]. Performance of metamaterial is related to its periodic arrangement. Periodically arranged structures increase the number of freedoms on the host structure; therefore, unique dynamic effects on filtering the wave propagation are observed [11]. Effective working conditions are classified using band terms: stop band and pass band. Wave propagation is blocked in any direction for the certain wave numbers which is called stop band. Outside of the stop band is pass band where the wave propagates in the media [12]. Proper calculations and applications may help to widen the stop band properties. Periodically arranged structures refer to infinite structure in the numerical studies. Infinite structures in the modelling would give better insight to structural behaviour under various working conditions. However, computational cost of this work is inconvenient. There are several periodic conditions ready to apply on the structures; Bloch - Floquet Theorem is one of the convenient methods. Bloch – Floquet

Theory provides infinite structure modelling on a finite structure using unit (elementary) cell identification. Applying the boundary condition around the unit cell maintains the finite element solver to recognise the unit cell as an infinite structure. Therefore, potential effects of metamaterials, periodically arranged structures and availability of bandgaps are questionable with infinite structural modelling.

This paper proposes the widened application range of PDs adding metamaterial properties to them. Particle behaviour under various excitation conditions were studied experimentally. The nonlinear effects of PD were observed. DEM (Discrete Element Method) was used to perform PD numerical study for a single frequency to understand the damping properties of particles. This was followed by the design of metamaterial made of periodic arrangement of PD. The casing of the damper was designed to resonate at one of the beam natural frequencies. Vibro-acoustic interactions were studied with finite element model. Bloch - Floquet Theory was applied to the modelled unit cell with singly periodic conditions.

2. METHODOLOGY

2.1 Experimental setup

In order to achieve the aimed application of PD and metamaterial, experimental and numerical studies were followed. Damper cases were printed using 3D printing conventional additive manufacturing method with recycled plastic material. Single sized stainless-steel particles (diameter of 1/16 inches) were used in the experimental studies to fill the volume of the damper casing. A fixed-fixed end conditioned structural steel beam was used for the experimental studies. SigLab Measurement Structure was used in the experimental studies: VNA (Virtual Network Analyser) and VSS (Virtual Swept-Sine) are the post-processing methods used to identify the system characteristics and running the experiments for the given sinusoidal excitation over a range of frequencies, respectively. Beam-shaker test (Figure 2.1) procedure was followed, and properties and effects of PD were studied. 60-150 Hz frequency range was selected to run the experiments; since this range contains the first bending mode of the beam.



Figure 2.1: Experimental rig with PD

2.2 Numerical modelling

2.2.1. DEM

Physics of densely packed solid particles and their dynamics were modelled with commercial software EDEM V19.1. The software works with the explicit process within defined time steps (iterations) while solving the contact physics of the related particles. Modelled structure has the same volume as the experimental structure. Filling fraction was converted into the number of particles for the modelling of simulation (Figure 2.2). Hertz-Mindlin contact theory was applied to the particle-particle and particle-wall

interactions. Rotational effects of the particles were modelled with the standard rolling friction method; since the normal and tangential forces acting on the particles and cavity were aimed to model. Aiming the consistency with the experimental studies, the excitation frequency of the simulations was held at 105 Hz.



Figure 2.2: Simulation model of DEM

2.2.2. FEM

Commercial software COMSOL Multiphysics V5.0 was used for modelling metamaterial.

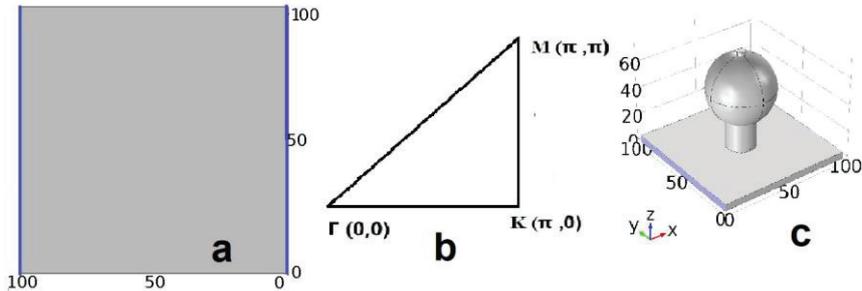


Figure 2.3: Periodic condition imposed in x- direction (a); Irreducible Brillouin Zone (b); unit cell with an inclusion (damper) (c)

To analyse periodic arrangement of PD casings and the effect of their resonance, different unit cell arrangements were modelled in COMSOL Multiphysics: (i) unit cell without attached damper case (only steel beam) and (ii) unit cell containing damper casing. The periodic boundary condition was applied either on single side or two sides of the elementary cell (Figure 2.3 (a)). Unit cell was modelled as a square with 100 mm length. The results were analysed in 1st irreducible Brillouin Zone (the smallest symmetrical lattice [13]) in form of dispersion relationship between wave vector and frequency.

3. RESULTS

3.1 Experimental Results

The first few bending modes of the beam discussed in previous section were observed experimentally at around 105 Hz, 325 Hz and 330 Hz and 580 Hz. The following arrangement of particle dampers mounted on the beam were tested experimentally: (i) single damper placed either at the centre or away from the centre, (ii) three dampers with various separation distance (L, in the graph).

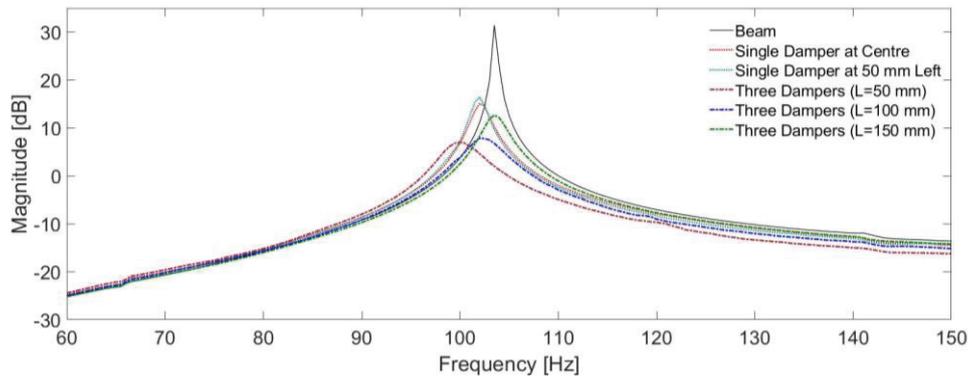


Figure 3.1: FRF of several cases with 65% filled dampers

Figure 3.1 shows the comparison between bare beam, single damper and three dampers with various lattice constant (shown in the Figure legend). The results were obtained at 0.1 V amplitude while the dampers were filled 65% of their volume with particles. As the number of dampers placed on the beam was increased, the FRF magnitude level was reduced. Natural frequency was also shifted to lower frequency. The observed shift was relatively small resulted in maximum 10% difference (observed for 3 dampers separated by 50 mm distance). It is noted that the mass of the dampers was much smaller compared to the beam. Hence, the frequency shift is expected to be small. It is also noted that due to the relatively small separation distance in the case of multiple PDs any periodic effect is expected to be observed at higher frequencies.

Amplitude dependency of the first natural frequency is shown in the Figure 3.2 (a) and (b). Both Figures clearly demonstrate the highest response level measured between 0.01 V and 0.03 V. For both arrangements the amplitude levels between 0.04 V and 0.08 V were the lowest response region. However, it is clear that three-PD arrangement gives much higher damping effect. It is also noted that nonlinearity phenomenon observed for a single damper are supported by previous studies [13], [14].

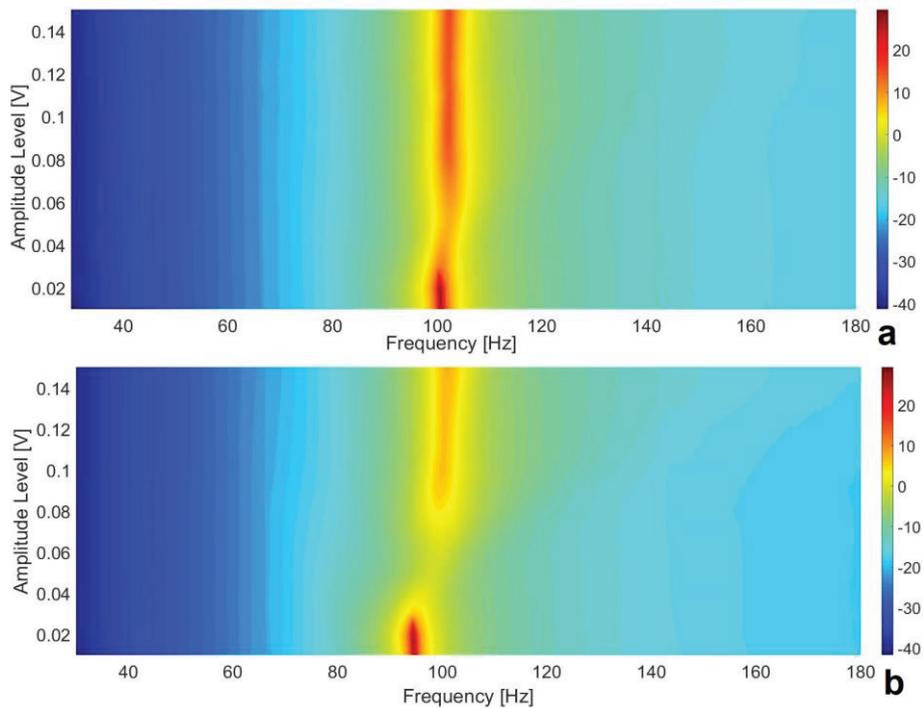


Figure 3.2: Amplitude dependency of single damper placed at the centre of the beam (a); Amplitude dependency of three dampers (L=50 mm) with 65% filling ratio (b)

3.2 Numerical Results

EDEM V19.1 was used to model and to solve densely packed solid particles to observe the particle behaviour in the simulation. Figure 3.3 demonstrates the relationship between the kinetic energy (associated with dissipated energy) and total energy. Each collision consists of impact and friction effects; therefore, the dissipated total energy is a combination of them. The total duration of numerical test was five seconds which has four seconds of collision and one second of placing the particles into the cavity and their resting at the end of the first second. Energy was dissipated through the collisions and contact mechanisms in the last four seconds of time. This information can be used to estimate losses and nonlinear phenomenon so that PD can be modelled accurately in FEM.

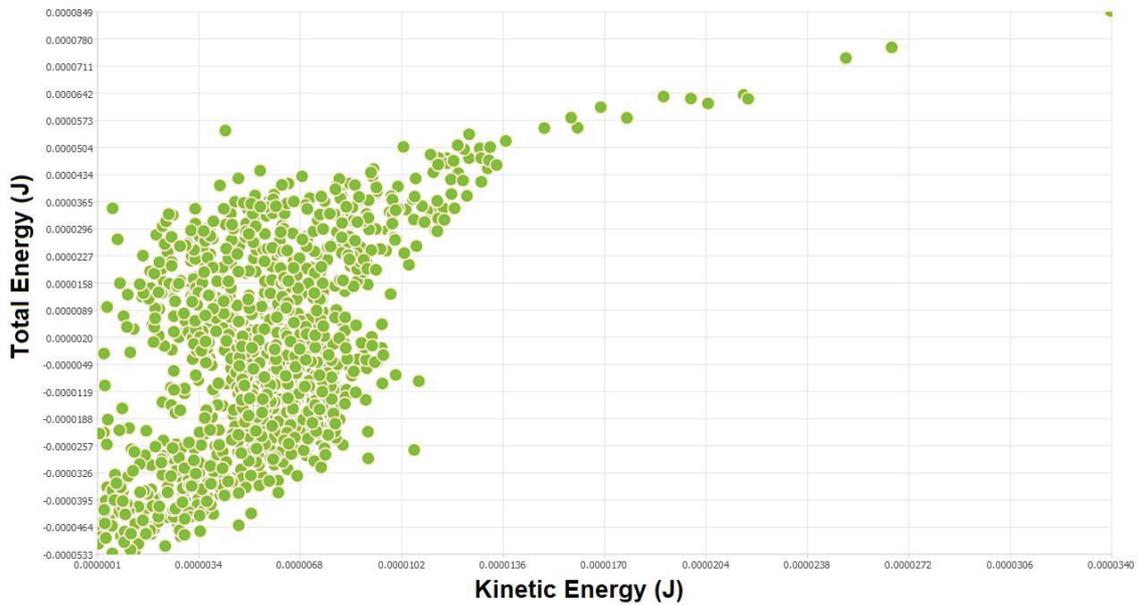


Figure 3.3: Energy dissipation of PD from DEM analysis

Bloch - Floquet Theory based infinite structure analysis were conducted to express the acoustic dispersion relations with single periodicity results. The results are shown in Figure 3.4. According to the Figure 3.4 (b) damper casing changes the dispersion relationship adding more low frequency modes bandgaps. More than one bands start from $k=0$ in the graphs; in an unbounded elastic medium there should be two modes starting from $k=0$. For the case of thin beam one additional modes appear for $k=0$ and there are more than three modes for $k=2$ [14]. The absence of the band in the dispersion diagram is called as bandgap, if it is the case for all the wave numbers then it is called as complete bandgap.

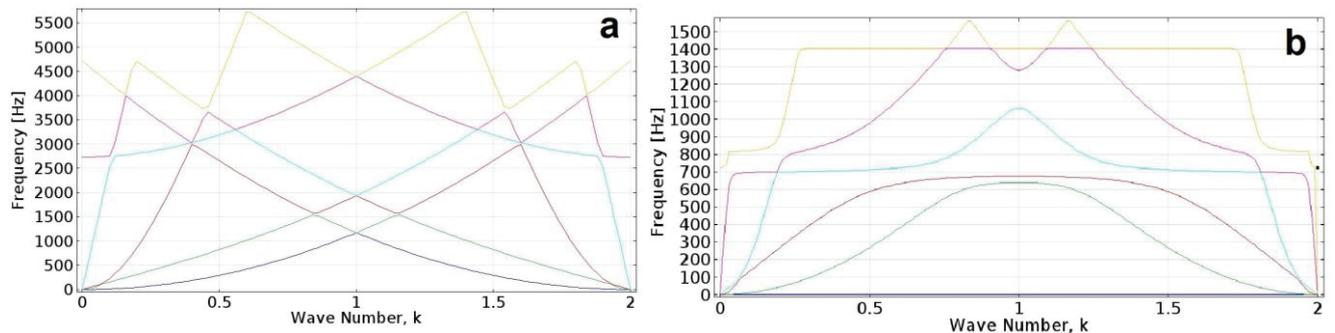


Figure 3.4: Dispersion relationship plotted for 1D lattice in form of solid beam (a) and periodic array of damper casing added to the lattice (b)

4. CONCLUSION

Nonlinear passive damping method was shown with its limitations including nonlinearity and effective working properties on the SDOF system running shaker tests. Numerical methods were followed to validate the studies related to both PD and metamaterial. Periodic arrangement using unit cell with the inclusions were illustrated here. It was shown numerically that these arrays support low frequency bandgaps. This study supports the idea that PD can be converted into metamaterial. DEM and FEM comparative studies are currently in progress.

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