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# Optimization of linear zigzag insert metastructures for low-frequency vibration attenuation using genetic algorithms

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## ABSTRACT

Vibration suppression remains a crucial issue in the design of structures and machines. Recent studies have shown that with the use of metamaterial inspired structures (or metastructures), considerable vibration attenuation can be achieved. Optimization of the internal geometry of metastructures maximizes the suppression performance. Zigzag inserts have been reported to be efficient for vibration attenuation. It has also been reported that the geometric parameters of the inserts affect the vibration suppression performance in a complex manner. In an attempt to find out the most efficient parameters, an optimization study has been conducted on the linear zigzag inserts and is presented here. The research reported in this paper aims at developing an automated method for determining the geometry of zigzag inserts through optimization. This genetic algorithm based optimization process searches for optimal zigzag designs which are properly tuned to suppress vibrations when inserted in a specific host structure (cantilever beam). The inserts adopted in this study consist of a cantilever zigzag structure with a mass attached to its unsupported tip. Numerical simulations are carried out to demonstrate the efficiency of the proposed zigzag optimization approach.

## 1. Introduction

While lightweight materials and thinner structures are important aspects of the structural design in the 21st century, the outcome of such design is predominantly flexible structural members with smaller damping and lighter mass. These structures are more effected by vibrations generated by the humans, machinery and the environment [1–5]. As a result, there is a growing need for designing and implementing innovative vibration suppression techniques to improve the serviceability and extend the structural life.

Recently, a new class of high-damping structural members referred to as metamaterial inspired structures (or metastructures) have started to be studied by the researchers. Metamaterials are artificial materials manufactured by injecting low-dimensional impurities into a certain material in a periodic fashion. The presence of such impurities significantly affects the wave propagation through the material resulting in exceptional material characteristics that are not found in nature. For instance, electromagnetic metamaterials exhibit unique behaviors including negative index of refraction, negative

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permeability, and electromagnetic bandgaps [6,7]. Additionally, acoustic metamaterials are commonly used to control the propagation of acoustic waves in order reduce sound transmission, noise and mechanical vibrations. The resonance of local material phases within acoustic metamaterials results in frequency bandgaps in the response of such materials. Acoustic waves passing through the material within the frequency range of these bandgaps are significantly suppressed [8].

By applying the concepts of acoustic metamaterials in the macro-scale, a new class of structures referred to as metastructures has been introduced. Typically, a metastructure consists of a host structure coupled with a number of spatially distributed structural subunits (i.e. inserts). When a metastructure is subjected to vibration, the inserts along the structure resonate locally resulting in bandgaps within the frequency response of the structure. The locations and bandwidths of these frequency bandgaps are directly related to the resonance frequency of the inserts. Therefore, the vibration suppression characteristics of metastructures can be adjusted as needed by altering the properties of the structural inserts.

Initial studies on metastructures have addressed the use of basic types of periodic inserts for vibration suppression. For instance, Pai [9] and Sun et al. [10] studied the vibration control of beams using uniformly distributed 1-DOF oscillators. Similarly, Pai et al. [11] used periodic two-mass spring-mass-damper inserts for the same purpose. These studies have shown great promise regarding the vibration suppression capabilities of metastructures. Their results demonstrated that the frequency bandgaps of metastructures are dependent on the distribution and resonance frequencies of the internal inserts.

Researchers have also investigated more sophisticated and realistic designs of inserts. Chiral lattice inserts are one of the most interesting examples that have been utilized in vibration attenuation applications. Initial studies on chiral inserts have demonstrated that significant energy absorption properties and low-frequency bandgaps can be achieved by using such inserts [12,13]. Baravelli and Ruzzene [14] utilized chiral lattice inserts for passive vibration control of a cantilever frame. The inserts used in their study consisted of annular steel masses connected by a network of ligaments made of a rubber-like material. It was shown that the vibration response of the flexible frame has been efficiently suppressed especially when using non-periodic chiral inserts (i.e. chiral inserts in which the radii of the mass inclusions and the spacing between them are non-uniform). In a similar study, Shiyin et al. [15] analyzed the vibration suppression performance of trichiral lattices. They found that these inserts display significant vibration attenuation and wide bandgaps. Additionally, in a recent study, Abdeljaber et al. [16] have developed an automated Genetic Algorithm (GA) based process for geometry optimization of non-periodic chiral inserts. The numerical simulations have demonstrated that the graded chiral designs obtained by this optimization method exhibit superior broadband vibration attenuation properties. Also, chiral lattices have been used by Ranjbar et al. [17] in vibracoustics applications.

However, there are some issues facing the implementation of chiral lattice inserts in vibration suppression applications. First, chiral inserts are inherently limited in terms of size and frequency due to the fact that the length of the ligaments is restricted by the dimensions of the host structure. When the ligaments are not long enough, their resonance frequencies will be significantly higher than the frequency range of ambient vibration, which makes them inefficient for vibration attenuation. Second, due to the complexity of non-periodic chiral-based inserts, it is challenging to formulate a closed-form analytical model for this type of inserts. Alternatively, finite element modeling is used to simulate the behavior of these inserts. However, using this modeling approach requires more computational effort and time. Hence, searching for an optimal graded chiral design either by trail-and-error or by an automated optimization approach is a time consuming process. Finally, it is relatively difficult to manufacture graded chiral inserts due to their geometric complexity.

Due to the drawbacks associated with chiral inserts, researchers are looking for more efficient and simple alternatives. Zigzag inserts are one of the most promising candidates in this field. Previous studies have shown that cantilevered zigzag structures have significantly lower natural frequencies compared to simple cantilevered beams [18]. Consequently, using zigzag inserts in metastructures is expected to provide low-frequency bandgaps, and therefore an efficient ambient vibration attenuation. Originally, zigzag structures were developed to be used in broadband low-frequency energy harvesting applications [19,20]. Later, Hobeck and Inman [18] conducted a preliminary study on the application of zigzag inserts for passive vibration control. The results have shown that considerable vibration reduction has been achieved when attaching the zigzag inserts to a flexible cantilever beam. Furthermore, it was experimentally demonstrated that introducing nonlinearity to the dynamic response of zigzag inserts by the use of magnets significantly improves the vibration attenuation properties of the host metastructure.

As shown in Fig. 1, the geometry of zigzag inserts is governed by several parameters including the number of segments as well as their length, width and thickness. Also, the natural frequencies of zigzag inserts can be easily adjusted by attaching masses at their free ends. Therefore, the tip mass is another important parameter that affects the response of zigzag resonators within a metastructure. The bandwidth and location of frequency bandgaps associated with zigzag inserts can be tuned by manipulating the aforementioned parameters. Hence, the study presented in this paper aims to develop an automated GA-based technique for optimization of zigzag inserts. The objective of this optimization procedure is to search for optimal zigzag designs that would minimize the ambient vibration response when incorporated in a particular metastructure. Owing to their ability in dealing with complex and insufficiently understood problems, Genetic Algorithms are used for finding the optimal zigzag parameters. The efficiency of the proposed optimization technique is demonstrated by both analytically and numerical simulations.

The significance of this research can be summarized in the following points:

- While the vibration suppression performance of zigzag inserts has been previously evaluated [18], this paper presents the first attempt to optimize these inserts in order to maximize their vibration attenuation performance.