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A metamaterial design for structural vibration mitigation exploiting geometrically nonlinear behaviour

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1 INTRODUCTION & SCOPE OF WORK

Mitigation of engineering vibration has been in the foreground of research that is concerned with structural safety. Perhaps, the most challenging hazard that can pose a threat to structural capacity and safety is earthquake excitation, which typically entails a low frequency content. This property inserts extra challenges in the application of metamaterials, which were initially applied for high frequency wave manipulation (Bilotti & Sevgi, 2012). Metamaterials are natural or artificial configurations that exhibit extraordinary properties in terms of wave filtering and guiding, achieved via periodic arrangement of a fundamental design termed the unit cell. In the context of vibration mitigation, prevention of wave propagation within specific frequency ranges is pursued, a task which can be efficiently taken on by metamaterial solutions (Zaccherini et al., 2020). In order to maximize the frequency range within which wave propagation is prohibited, the so-called bandgap, nonlinear unit cell designs are here explored. One such solution is delivered via exploitation of geometric nonlinear behaviour, which updates the system's stiffness properties depending on the level of experienced displacement. We show that suitable utilization of such response can offer great potential towards vibration mitigation on structures.

2 METHODOLOGY

In this study, geometrically nonlinear behaviour is investigated within the unit cells of the configuration. These are formed following the work of Chondrogiannis et al. (Chondrogiannis et al., 2021), by a mass m that is connected to a mass μ via a nonlinear element. The nonlinear element is formed by the arrangement of 2 linear springs of stiffness k_n to a triangular arch setup, as shown in Figure 1. Under large displacements, the setup produces geometrically nonlinear behaviour due to change in the angle of the springs and subsequent change in the equivalent stiffness of the configuration. Negative stiffness effects can also be generated for specific displacement values, as a result of such a bi-stable system (Al-Shudeifat, 2014).

Focusing on the nonlinear element of the unit cell, it is important to study its equilibrium path. This follows a nonlinear relation, as discussed in the work of Al-Shudeifat (Al-Shudeifat, 2014). This relation is further approximated with a 3rd order polynomial (Al-Shudeifat, 2014), used for the calculation of the dispersion curves. These curves are calculated analytically according to Chondrogiannis et al. (Chondrogiannis et al., 2021) after applying periodic boundary conditions in the context of the infinite lattice, and the resulting bandgap is specified, as shown in Figure 1. This attenuation zone is depended on the relative oscillation amplitude $|V_1|$ of the nonlinearly connected masses, shifting both the acoustic and optical branch in the frequency domain.

The effectiveness of the metamaterial configuration has been additionally evaluated upon its attenuation properties to a target structure. For this purpose, a 2-dimensional finite element model has been simulated via the Real-ESSI software (Jeremic et al., 2021), as shown in Figure 2. The protected structure is formed by a base frame and a vertical beam, at which a concentrated mass of 50Mgr is applied to the top end resulting to a

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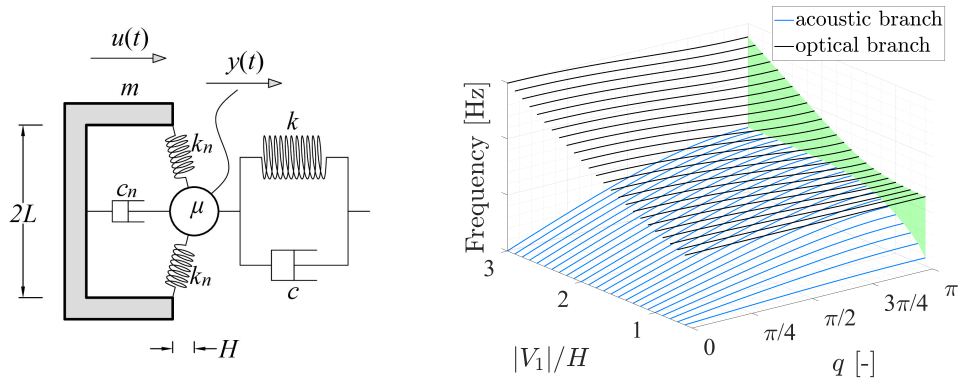

Figure 1. (*left*)-*Nonlinear unit cell,* (*right*)-*Dispersion curves of the infinite lattice.*

natural period T_n=0.4s, while 5% damping is considered. The metamaterial device is inserted between the basement of the structure and the surrounding soil in a 3x3 unit cell configuration at each side. The individual unit cells have dimensions of H=0.05m and L=0.5m, and therefore, the vertical arrangement of 3 cells covers the overall 3m height of the basement. The basement remains attached to the soil from below, therefore adding soil-structure interaction effects. The nonlinear device was simulated with linear elastic beam elements in triangular arrangement, where 2nd order effects are considered. Each cell has a mass of 1.3% of the total mass of the structure, which is calculated considering reinforced concrete material for masses m and μ (μ=m/2) with the aforementioned dimensions. The stiffness of the components was adjusted to k_n=3200kN/m and k>>k_n creating a bandgap opening frequency at around 1Hz for $|V_1|$~H, with the upper limit of the attenuation zone lying at high frequencies due to the high value of k. Subsequently, the resulting bandgap includes the resonant frequency of the structure for realistic oscillation amplitudes. The soil material is modeled considering linear elastic behaviour and is divided to a top soft layer of 15m thickness and a much stiffer lower one of 10m thickness, while damping is also applied. The application of the dynamic loading is performed with the use of the Domain Reduction Method (DRM) (Jeremic et al., 2021). It includes a single layer of elements (DRM layer) at which effective forces are applied. This results in simulation of a target accelerogram at a specified level of the model in the free field. Additionally, there exist surrounding damping elements that absorb waves, which are radiated from the local feature, and thus there is minimal interference of reflected waves within the soil domain. For the analysis of this work, actual earthquake records were applied, therefore the specified level of the target accelerogram is selected to be at the surface of the model.

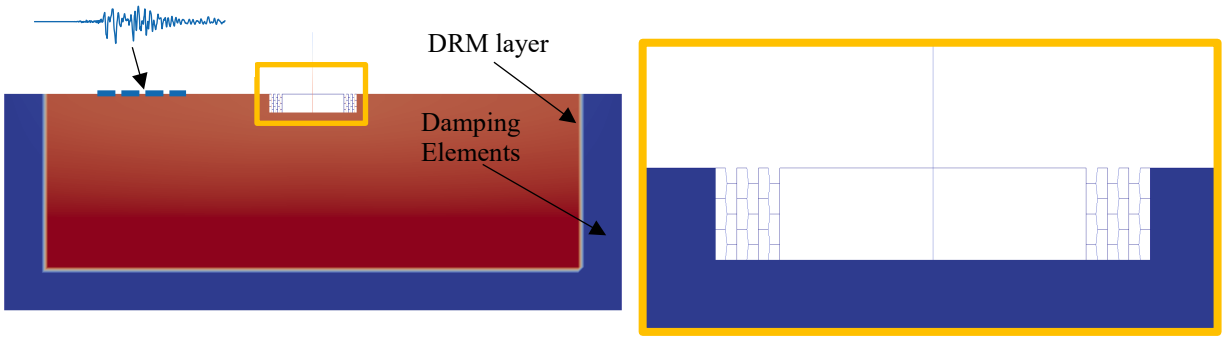

Figure 2. *Finite element model and application of the DRM.* (*left*)-*Overview of the 2D model,* (*right*)-*Close up to the metamaterial configuration and coupling with the structure.*

3 MAIN RESEARCH OUTCOMES

For the evaluation of the configuration's performance, numerical finite element analyses have been performed for the model including the nonlinear system, as discussed in section 2. For this purpose, dynamic simulations incorporating 2nd order effects are implemented. The JMA earthquake record (PEER Center, 2021) is applied to the surface of the model, which features a rich frequency content in the range around the resonance of the protected structure. Figure 3 depicts the cumulative strain energy at the base of the column of the structure calculated from Eqn. (1), which is a representative measure of damage. This measure should not be confused with the accumulated energy, which in this case is not present since the system is elastic. These results are

further compared to the unprotected case, where the soil material is in place of the metamaterial, as well as to an equivalent linear case where 2nd order effects are neglected. It is observed that the nonlinear configuration can offer a significant reduction to the energy of the protected system compared to the unprotected case, while the equivalent linear system can't offer any worthy reduction. In this case, it is important that the protected structure remains connected to the soil at the bottom, thus establishing any reduction in the response considerably challenging. It is concluded that the nonlinear device can attenuate vibrations to the primary system even while the latter is not detached from the soil, therefore promising great potential for retrofitting purposes of existing buildings.

$$U_{cum}(t) = \int_0^t U(\tau) d\tau \tag{1}$$

where $U(t)$ denotes the instant strain energy at time t.

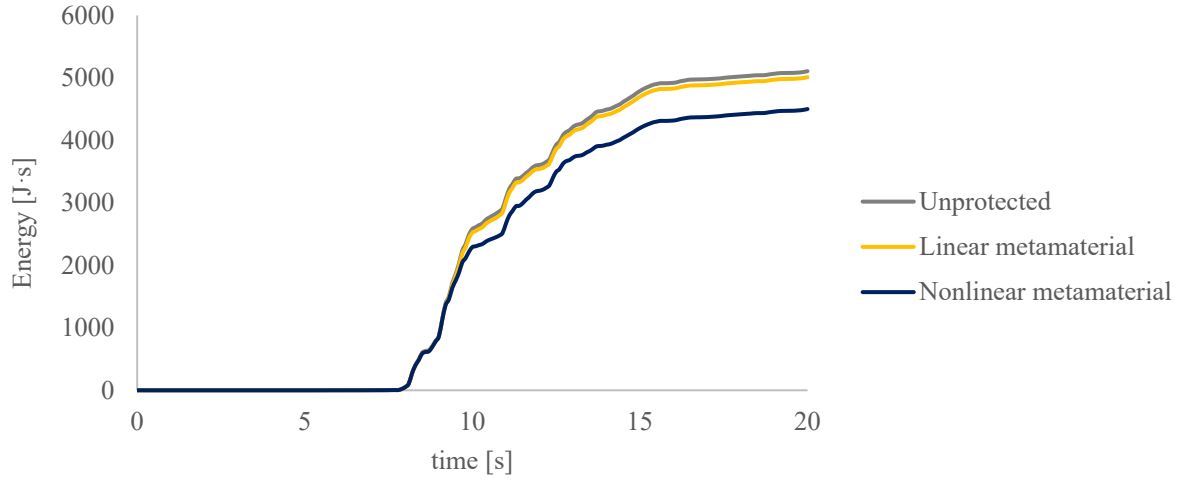

***Figure 3**. Cumulative strain energy at the column's base for the JMA earthquake record, comparing the protected cases with the nonlinear and equivalent linear metamaterial to the unprotected case.*

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