Energy exchange in a mass-in-mass meta cell with geometrically customized nonlinearity

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Abstract

Vibration is a prevalent physical phenomenon encountered across various engineering applications. Understanding and controlling vibrations in mechanical systems are of key concern as they affect the serviceability and overall performance of these systems. Excessive vibrations can compromise operational efficiency and may pose risks to sensitive equipment or individuals. Effective vibration control is especially important when the vibrations occur within critical frequency ranges. To address this, various passive control techniques are available. One widely used method is the tuned mass damper (TMD), which involves attaching a secondary mass with a prescribed mass ratio to the primary structure using linear spring-damper elements. While conventional TMD systems are effective, they have the limitation of reducing vibrations within a narrow frequency range, typically addressing only a particular mode due to their linear springs. An alternative approach is to employ nonlinear energy sinks (NES), which incorporate a nonlinear spring and, therefore, have an energy-dependent natural frequency. This unique characteristic allows the NES to sequentially mitigate multi-modal vibrations from high to low frequencies through resonance capture, making NES notably advantageous over traditional TMDs in controlling multi-modal vibration.

Creating nonlinear stiffness is the core to dynamic design of NES, often tailored to specific requirements and application scenarios. Depending on material properties and geometric configurations, there are several ways to form nonlinear stiffness. NES can generate or adapt to specific nonlinear force profiles are increasingly valuable as they allow tailored responses in systems subjected to complex dynamic loads. Among nonlinear force profiles, cubic and piecewise nonlinearity have garnered particular interest due to their versatile applications in systems requiring energy dissipation or vibration isolation.

This study presents an analysis and experimental validation of energy exchange in a mas-in-mass meta cell with a tailored nonlinearity. In this regard, a device specifically engineered

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§Corresponding author: Sebastien.Baguet@insa-lyon.fr to customize pure cubic and piecewise nonlinear forces, with potential applications in vibration isolation, frequency tuning and dynamic response control in various systems. The device is designed using a combination of mechanical springs, and uniquely curved mechanical stops. These components are arranged in a configuration that allows adjustment of the force-displacement relationship, resulting in customizable nonlinear force characteristics. The primary mechanism enabling cubic nonlinearity involves a carefully tuned spring system. The spring stiffness and pre-compression are adjusted to achieve a cubic relationship between force and displacement over a desired operational range. To generate piecewise nonlinear force, the device utilizes adjustable stops or mechanical stops with curvature that engage at predetermined displacement thresholds. These stops introduce abrupt changes in stiffness, which results in a force profile that switches between different stiffness values as the displacement reaches specified points. By adjusting the position of the stops and the stiffness of the springs, the force-displacement profile can be customized.

An experimental setup is constructed to validate the numerical results. The device is mounted on a vibration testing platform capable of providing controlled displacements and loads. Sensors are attached to measure displacement, force, and acceleration, allowing precise monitoring of the device's response to various input conditions. The experimental protocol includes tests for both pure cubic and piecewise nonlinear configurations, with multiple trials conducted to ensure repeatability and accuracy. The device is subjected to harmonic excitation over a range of frequencies and amplitudes. The resulting force-displacement curves are recorded and compared with the numerical model predictions.

The designed NES has significant potential in fields that benefit from tailored nonlinear dynamics. For instance, in vibration isolation, the cubic nonlinearity allows for higher energy dissipation and improved isolation at specific frequency ranges. Similarly, the piecewise nonlinearity could be utilized in shock absorbers, where a variable stiffness profile is necessary to handle impacts of varying magnitudes, ensuring efficient energy absorption over a wider frequency range. Additionally, this NES can be used in systems exposed to dynamic loads, such as bridges or buildings, where nonlinear damping mechanisms are beneficial for reducing resonance and prolonging structural life. Moreover, the proposed NES can be arranged in a chain of meta-cells to tailor wave propagation by creating periodic and non-periodic responses, enabling their use as vibro-acoustic filters. The device's ability to tailor force profiles makes it ideal for adaptive systems that require different force responses due to changing environmental conditions or operational demands.

This study successfully demonstrates the design, analysis, and experimental validation of a NES capable of generating pure cubic and piecewise nonlinear force profiles. The performance of the designed NES, particularly in terms of energy exchange, is verified through numerical modelling and experimental testing. This research establishes a foundation for developing advanced devices that leverage nonlinear dynamics for practical engineering applications, paving the way for more resilient and adaptable systems in various engineering fields. Furthermore, investigating the performance of the proposed NES under multi-directional or complex loading conditions presents a promising avenue for future research.