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A broadband damper design inspired by cartilage-like relaxation mechanisms

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A B S T R A C T

In this study, we introduce a broadband damper design inspired by the cartilage-like relaxation mechanisms. In particular, we study broadband (static to 10 kHz) dissipative properties of model cartilage systems by probe-based static and dynamic indentation, and validate that fractional Zener models can simulate the empirical data up to a desirable accuracy within the frequency range of interest. Utilizing these observations, we design a composite damper design where a poroelastic layer is sandwiched between two hard materials, and load transfer occurs across interfaces with multiple length scales. Modeling those interfaces with fractional Zener elements in parallel configuration, and manipulating the distribution of the Zener elements across different peak relaxation frequencies, we obtain a relatively constant loss factor within an unprecedented frequency range (*3-3* kHz). We also discuss how these findings can be employed in a practical damping design.

1. Introduction

Absorption and trapping vibratory energy within a broadband frequency is indispensable for most man-made systems. Traditional vibration attenuation methods include isolation from the loading source, and use of active or passive vibration absorbers, impedance mismatch (reflection and redirection of vibration energy), magnetorheological fluids and viscoelastic materials for damping [1]. Those techniques require costly and heavy sets of auxiliary materials and components, yet still lack broadband effectiveness. Cellular materials such as elastomeric or polyurethane foams provide excellent shock absorption at the expense of mostly irrecoverable buckling, crushing and collapse, and hence are not suitable for mitigating sustained vibrations [2]. More contemporary damper designs achieve broadband performance by incorporating two or more of the traditional methods in semi or fully active configurations. For instance, the “e-damping” idea by Wang and Inman presents an active broadband damper design combining piezo-ceramics, oxides, polymers and elastomers in a functionally graded multilayer composite [3]. Piezo-ceramics serve as sensors and actuators in this composite, and a closed loop controller compensates for dissipation in the polymer and elastomer layers dependent on the rate and temperature. Although this active damper design increases power consumption and overall weight, it promises effective damping across wide frequency bands relevant to structural vibrations (10–200 Hz).

Frequency band gaps obtained in metamaterials and structures offer an alternative vibration suppression mechanism by stopping wave transmission at certain frequency ranges. In properly designed metamaterials, periodic arrangement of

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resonators (lattices) add inertia to a host system, trap vibrations locally, and thus prevent wave transmission at certain frequency bands [4–8]. Numerous research groups have demonstrated broad frequency band gaps by using fractal, granular, particle and beam-based composite metamaterials [5,9–15]. Those frequency band gaps, however, reside at higher frequency ranges than structural vibrations (> 200 Hz). Several groups proposed composite metastructures with chiral and zigzag lattice geometries to localize the vibration energy and obtain effective band gaps relevant to structural vibrations [16,17]. Similar energy localization was shown to occur in dynamic systems consisting of fuzzy internal components with distributed natural frequencies [18–23]. Recent work optimizing the frequency distribution of fuzzy internal components provides experimental validation of enhanced suppression and damping performance for structural vibrations [24,25]. As in the metamaterials, these approaches require some form of dissipative interactions and/or viscoelastic materials to quickly and effectively dampen localized energy. Otherwise, reliability issues arise in the form of either structural failure at the lattice-scale or transfer of localized energy to the host structure after a short duration [20,26].

Recently, several research groups introduced a novel mechanism to enhance wave and vibration damping by adding negative stiffness to a dynamic system [27–29]. Chronopoulos et al. designed and applied negative stiffness inclusions into the composite metamaterials, and found several orders of magnitude increase in damping ratio in the low frequency range (100 Hz) [30]. Harne et al. introduced so-called hyperdamping metamaterials achieving broadband energy dissipation (up to 1600 Hz) [31,32]. Furthermore, Antoniadis et al. provide theoretical framework for the contribution of negative stiffness to broadband damping [33]. Those studies offer significant enhancement in damping magnitude, yet dismiss any discussion on rate-dependence.

In this work, we illustrate a composite damper design that yields rate-independent relaxation damping within a wide range of frequencies. This damper design is inspired by the broadband poroelastic relaxation in human and animal articular cartilage [34–38]. Poroelastic relaxations are already utilized in synthetic noise-absorbing materials, but damping efficacy in those materials is limited to high frequency excitations. Recent efforts attempt at expanding the bandwidth, especially to lower frequencies by active and passive composite systems [39–41]. One approach to ensure effective damping at both low and high frequencies is to embed mass inclusions with low resonance frequencies into the poroelastic matrix [40]. Embedded inclusions tend to move significantly under resonance conditions, and damping increases due to inclusion-matrix interactions at low frequencies. Combined with the high-frequency poroelastic relaxations, those composite dampers achieve effective damping at both ends of the frequency spectrum. Our composite damper design can be seen as an extension of this idea to continuous patch of materials rather than discrete masses. In particular, our study will demonstrate that energy dissipation in cartilage-like coatings and interfaces with hard materials spans wide frequency bands, and sandwiched damper designs with multiple contact interfaces can be optimized for rate-independent damping. Rate-independent broadband damping enables both energy absorption and mathematical tractability, and therefore offers the most ideal characteristics for structural dynamics and acoustics applications [42,43]. In the rest of the paper, we will first revisit simple mechanical models and discuss their relevance to the interfacial mechanics of poroelastic half space-hard indenter contact. Then, we will obtain rate-independent broadband damping system by optimizing the contact patches and material properties. The assumptions and expansion of the model will be discussed at the end of the paper.

2. Problem description

2.1. Damping in poroelastic interfaces

In this work, we mimic the broadband dynamic response of cartilage by a composite damper consisting of a swollen poroelastic (PE) layer sandwiched between hard plates as shown in Fig. 1. The lower plate acts as a substrate upon which the PE layer reside, and the upper plate includes spherical protrusions with different radii contacting the PE layer. A dynamic stress (strain) is applied to the PE layer and the strain (stress) is monitored. The phase difference between the stress and strain is employed in quantification of damping. Our first claim is that one can model the dissipative properties of such a multiple contact interface system with multiple fractional Zener models shown in Fig. 1. We will validate this claim by studying the single interface consisting of a hard spherical probe pressed on to PE layer. After the validation, we will use the multiple fractional Zener model representation to obtain optimal damping.

2.2. Modeling of single interface

2.2.1. Relaxation of single fractional Zener model

We will use a fractional Zener model (FZM) (Fig. 2(b)) to simulate the single contact interface between a hard (rigid) spherical probe and a poroelastic half space shown in Fig. 2(a), and analyze the poroelastic relaxation and broadband dissipation properties of this interface.

Stress-strain relations of a FZM can be derived as

$$\sigma + \tau_\sigma \frac{d^\alpha \sigma}{dt^\alpha} = M_R\left(\varepsilon + \tau_\varepsilon \frac{d^\alpha \varepsilon}{dt^\alpha}\right) \tag{1}$$