# Integration of Piezostacks as Frequency Dependent Stiffness Elements in Load Bearing Structures

**Conference Paper**

**Author(s):**
Schmied, Jascha U.; Bergamini, Andrea

**Publication date:**
2019-07

**Permanent link:**
https://doi.org/10.3929/ethz-b-000371943

IX ECCOMAS Thematic Conference on Smart Structures and Materials
SMART 2019
A. Benjeddou, N. Mechbal and J.F. Deü (Eds)

# INTEGRATION OF PIEZOSTACKS AS FREQUENCY DEPENDENT STIFFNESS ELEMENTS IN LOAD BEARING STRUCTURES

**Jascha Schmied***, **Andrea Bergamini**†

* CMASLab, ETH Zurich, Leonhardstrasse 21, CH 8092 Zurich, Switzerland
e-mail: jschmied@ethz.ch

† Acoustics / Noise Control, Empa, Überlandstrasse 129, CH 8600 Dübendorf, Switzerland
e-mail: andrea.bergamini@empa.ch

**Key words:** piezodamping, local resonators, coupled resonators, piezostack

**Abstract.** In previous work we have described the use of piezoelectric elements as means to obtain variable connectivity between the elements of a phononic crystal by exploiting the frequency dependent stiffness of resonantly shunted piezoelectric elements. There, piezoelectric disks were intercalated between an aluminum plate and aluminum stubs and were used to effectively disconnect the stubs creating a phononic structure from the substrate. Given the function of the investigated object, no special structural requirements were set to the piezoelectric disks. Here, we present work related to the structural integration of piezoelectric elements in a load bearing structure. The goal of the integration is to exploit frequency dependent stiffness properties of resonantly shunted piezos to modify the stiffness matrix of a simple truss structure. In order to demonstrate the proposed approach, a ring-shaped piezo-stack is axially mounted into the diagonal strut of a square frame. In order to guarantee the function of the piezoelectric element under the expected load conditions, axial pre-compression needs to be applied. This contribution describes the design, implementation and initial investigation of the dynamic response of a variable connectivity truss structure.

## 1 INTRODUCTION

The use of shunted piezoelectric elements for vibration damping purposes has now been demonstrated [1] for four decades, further developed and divulged in innumerable contributions [2, 3, 4, 5] and represents in some ways the golden standard in integrated multi-field vibration mitigation treatments. However, the implementation of this type of treatments implies the ability to correctly tailor the position and frequency response of the piezoelectric device and is subject to detuning or incorrect placement of the shunted piezoelectric element due to varying operational conditions, deterioration of the integrity of the structure or environmental effects. As such, in spite of their undoubted efficacy, their practical application is still limited to very specific cases. Recent research indicates that under certain conditions, the implementation of distributed elements for the mitigation of mechanical vibrations can offer substantial advantages in terms of robustness of the system. In this sense, with the understanding that structural vibrations are nothing else than the expression of the interaction of low frequency waves propagating through a structure and interacting with its boundaries and the imposed conditions, the focus of research is shifted to avenues for the manipulation of the propagation of mechanical waves. Here, the groundbreaking work of Liu [6] has successfully demonstrated the wavenumber-independent attenuation of mechanical waves at a specific frequency using sub-wavelength features, employing local mechanical resonators and providing for robustness against the misplacement of the energy absorbers within the structure. Inspired by these findings, elegant implementations of local resonators based on electromechanical systems were devised, such as the ones presented by Spadoni [7], and Casadei [8], among others. This approach to wave propagation control offers the undoubted advantages of wavenumber independent attenuation of waves and orthogonality to structural properties [9] originating from the local nature of the resonators, however at the cost of a very narrow band effect. Wu [10] has demonstrated the realization of complete Bragg bandgaps in macroscopic systems, echoing the seminal work of Brillouin [11] on the propagation of waves in periodic media. Here it has been shown that in periodic arrangements of mass and spring elements the propagation of waves in certain ranges is suppressed by scattering phenomena. This effect can cover wide frequency ranges [12, 13, 14]. As long as the modulus, density, unit cell size of the phononic crystal allow for it, the position of the bandgaps can be positioned at arbitrarily low frequencies. However, it should be noticed that there are limits to what can be achieved in these terms [15]. In previous work we have shown a possible use of electromechanical resonators as variable stiffness elements to modify the connectivity in phononic crystals [16]. There, we introduced resonantly shunted piezoelectric disks between the stubs and the plate of a stubbed plate as described in [10]. If the resonance frequency of the piezoelectric element was position within the Bragg type bandgap created by the lattice created by the periodically arranged stubs, we could observe the appearance of a passband. We interpreted this observation as due to the effective modification of the connectivity of the stubs and the plate, due to the frequency dependence of the effective modulus of the piezoelectric disk around the electric resonance of the LC shunt. In this contribution we explore the implementation of frequency dependent stiffness elements (embodied by resonantly shunted piezoelectric elements) in lattice-type phononic crystals, as a way to adaptively modify the connectivity of the lattice, with the expectation that some useful property would emerge from this. The baseline expectation is that, the adaptive connectivity of the lattice can be used to strongly affect its response to dynamic loads. Here we present a numerical investigation of dynamic properties of a lattice structure with adaptive connectivity trusses and of the unit cell it is made of. Finally, we show the state of advancement of our effort to experimentally verify the behavior predicted by our models.

## 2 STRUCTURES WITH FREQUENCY-DEPENDENT STIFFNESS ELEMENTS

The implementation of active elements in truss structures has been presented in [17], where the effectiveness of discrete piezoelectric elements in an active vibration suppression scheme is outstandingly demonstrated. Here, we will discuss a passive approach, in which piezoelectric elements are implemented as frequency dependent stiffness elements. First, we will investigate the frequency response of the base element of the two-dimensional structure, that we will consider as the unit cell of a periodic structure and assess the frequency dependent stiffness of the unit cell (see fig. 1). Then we will show the effect of distributed frequency dependent elements in a periodic structure (see fig. 2) on its frequency response. The frequency dependent stiffness elements are represented by bulk piezoelectric elements in the numerical models presented in the following sections, for the sake of simplicity. Accordingly, the inductance values selected to obtain the electrical resonance of shunts at the frequencies of interest are very high. In the practical implementation, briefly discussed at the end of this work, piezostacks are chosen, over piezoelectric patches as a more effective way to exploit the electromechanical coupling in a load carrying structure. The simplification made in the numerical models does not affect the validity of the general findings they provide.

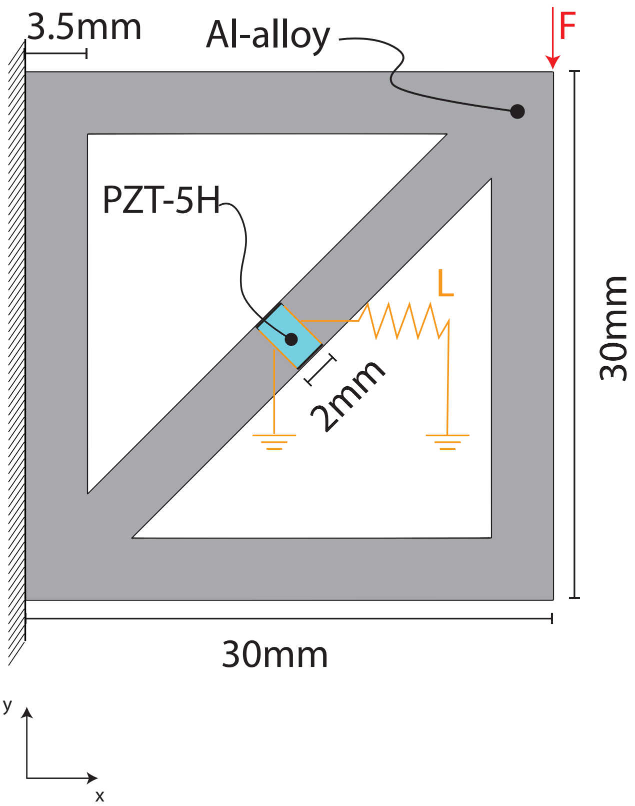


**Figure 1**: Base unit of the truss structure with frequency dependent stiffness elements, consisting of a diagonal brace, in which a piezoelectric element shunted over an inductor $L$ is integrated, horizontal beams, and vertical beams to close the frame. In the model, the unit cell is fixed along its left edge.

### 2.1 Unit Cell

In two dimensions, a square frame with a diagonal shear stiffening element represents a very simple component from which a larger structure can be created by simple symmetry operations such as translation, rotation, and mirroring. The properties of such a structure are known to carry the imprint of its constituting components [18]. So, we are interested in understanding the effect of the electrical resonance in the shunted piezo on the dynamic properties of the unit cell. Assuming that the shunted piezoelectric element provides the frequency dependent stiffness postulated in [16], we can expect the shear stiffness of the truss to strongly vary as a function of frequency, around the resonant frequency of the piezoelectric resonator. The host structure is modeled in COMSOL Multiphysics as a two-dimensional object, assuming plain strain conditions, with an assigned thickness (z-direction) of 3.3mm. The host structure (grey) is modeled as an aluminum alloy, the piezoelectric element representing a piezoelectric stack is taken to have the properties of PZT-5H. The dimensions and the mechanical boundary conditions are shown in figure 1. A point force in -y direction is applied to top right corner of the unit cell.

### 2.2 Structure

The structure we consider is inspired by the unit cell discussed above. The diagonal braces with the integrated piezoelectric element are identical with the one implemented in the unit cell. The horizontal

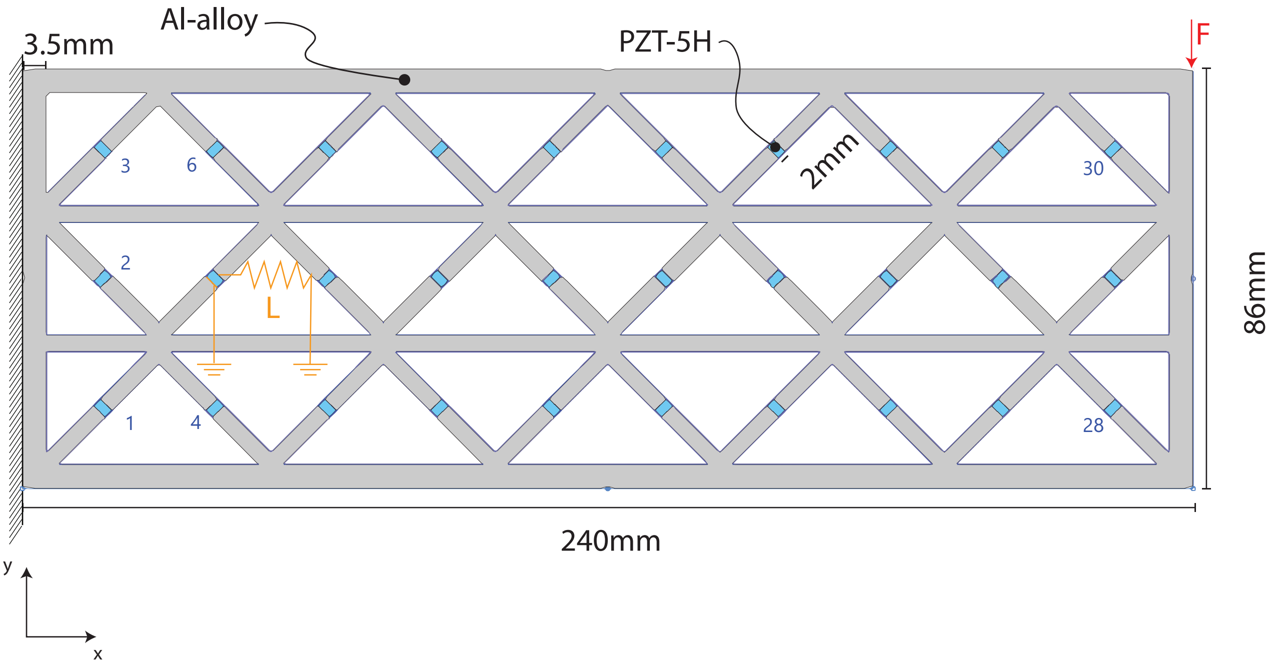


**Figure 2**: Structure that includes diagonal braces as discussed in the previous section. Additionally some horizontal beams are added to maintain the free length of the braces. The width of the outer frame is the same as in figure 1. The figure shows only one electric shunt (inductor L=210.5H), implying that each piezoelectric element is shunted individually over identical circuits. The numbers in blue color, next to the piezos, indicate the numbering scheme for the piezoelectric elements.

trusses have the same width as the quadratic frame of the unit cell, while the frame of the structure is slightly wider. In order to be able to include periodic arrays of braces with the same length as in figure 1, horizontal elements were included. The resulting structure is presented in figure 2. As in the model presented in the previous section, the left edge of the structure is fixed both in x- and in y-direction. The materials considered in the 2-dimensional model of the structure are the same as for the unit cell. The model also assumes plain strain conditions and has an assigned thickness of 3.3mm. A point force in y-direction is applied to top right corner of the unit cell.

The frequency response of the two structures described in the sections above, represented as the displacement amplitude for a unit force applied to the structure and the time average of the electric energy density within the piezoelectric elements will give us information about the effect of the the integrated variable stiffness elements on the dynamic response of the two structures.

## 3 RESULTS and DISCUSSION

In the following we report the displacement-amplitude recorded at the position where the point force is applied as a function of frequency for three different electrical boundary conditions applied to the piezoelectric elements: open circuit, where no current can flow in the shunt, short circuit, where the potential between the electrodes is zero and where the impedance of the shunt is determined by an ideal inductor with $L = 210.5H$. The reported quantity represents the compliance of the structure, with the units [mm/N]. For the same boundary conditions, we report also the time averaged electrical energy density in the piezoelectric elements, as a measure of the energy exchanged by the structure with the

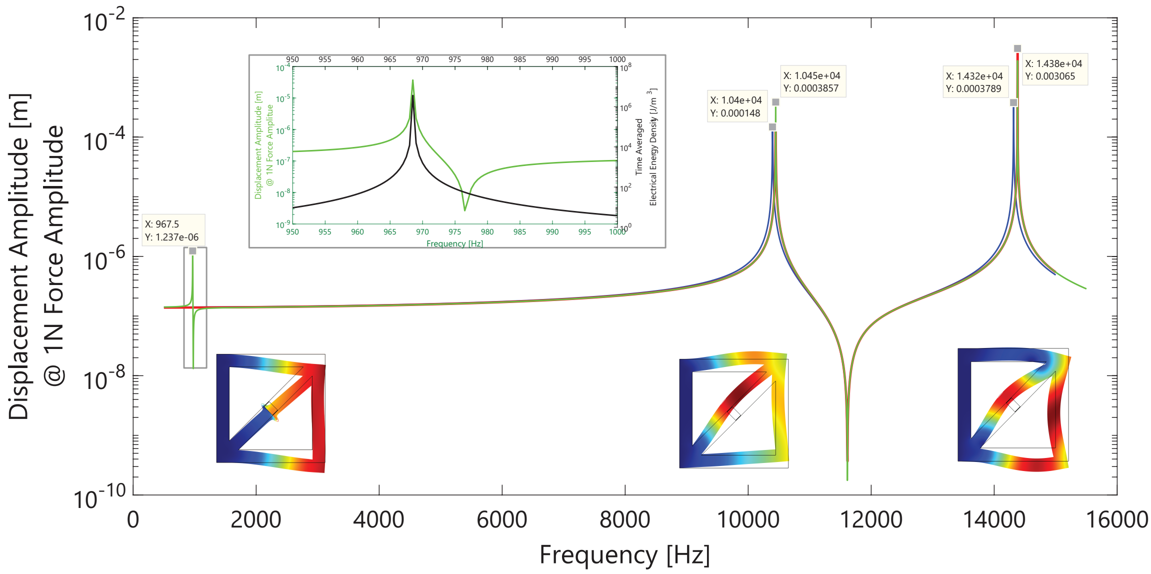


**Figure 3**: Overview of the frequency response (green, displacement amplitude) of the unit cell under open circuit, short circuit and inductively shunted ($L = 210.5H$) conditions, the color figures show the modal shapes for the corresponding eigenfrequencies, the insert shows a detail of diplacement and electrical energy density (black) in proximity of the eigenfrequency of the LC resonator (shunted piezo).

shunted piezos.

### 3.1 Unit Cell

The frequency response of the unit cell, expressed as its compliance, well agrees in its essence with the results reported in [16]: The stiffness of the piezoelectric element is known to drop at frequencies immediately below the resonance frequency of the LC shunt and to increase again as the frequency exceeds it, accordingly the compliance of the structure increases and decreases again to values similar to the ones far away from resonance. Also the comparison between open and short-circuit boundary conditions confirms what we know: It is reasonable to state that -unsurpriingly- also in the configuration presented in this work, piezoelectric elements can be regarded as elements that can change their effective stiffness as a consequence of the electric boundary conditions.

### 3.2 Structure

The integration of shunted piezoelectric elements in a larger, periodically arranged structure is expected to carry in itself to a large extent the footprint of its constitutive elements. If in the piezoelectric elements a variation of the stiffness of the components occurs at a specific frequency, the effect of this variation can be expected to affect also the behavior of the larger structure. Now, since under the ideal conditions offered by a numerical model, we were able to tune all LC circuits composed of the piezoelectric element and the inductor to the same frequency (approximately $484Hz$ for the given piezos and an inductance value of $L = 842H$), the expectation would be to see an increase in compliance, i.e. of displacement amplitude in correspondence to the electric resonance, similar to what we see for the unit cell comprised of one piezoelectric element. This corresponds also to the observation made for local

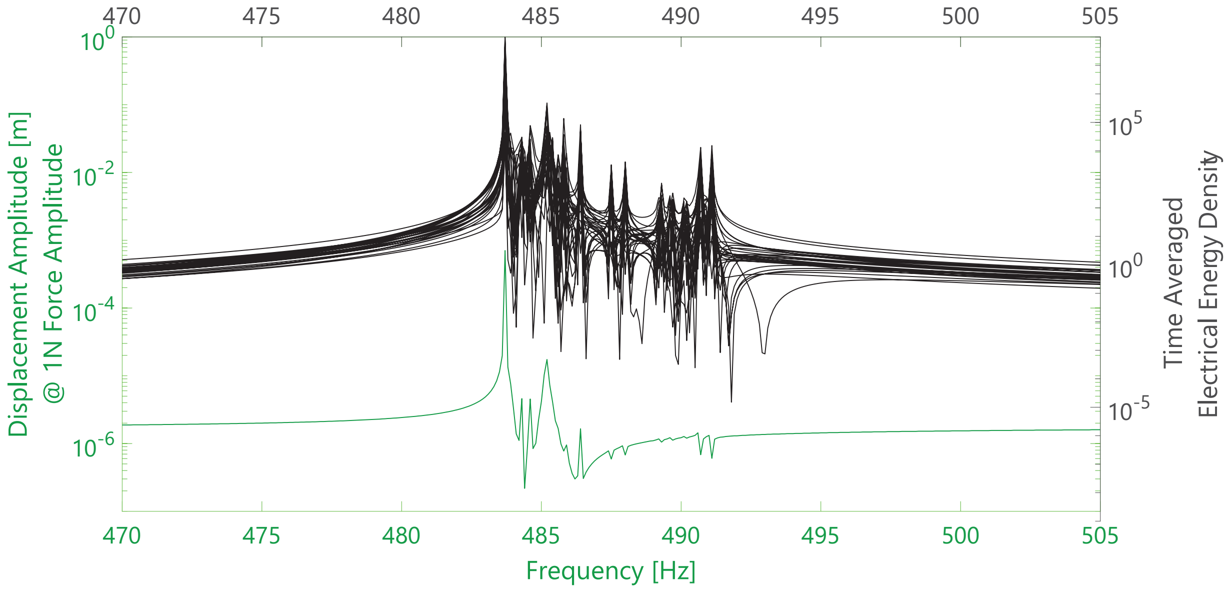


**Figure 4**: Frequency response (displacement amplitude, black, and time-averaged electric energy density in the piezoelectric elements, colors) of the unit cell under inductively shunted ($L = 842H$) conditions at frequencies below the first global, structural eigenfrequency ($968.5Hz$).

piezoelectric resonators, as discussed in [8, 7], where a dip in the transmissibility of waves through the structure. Here, however, we observe phenomena that qualitatively and quantitatively deviate from the response of a single or of an array of *local* resonators: in stead of a single peak and subsequent dip in compliance, the frequency response of the structure at hand shows a much richer behavior, spanning over a fairly wide range of frequencies, and characterized by a series of local displacement amplitude peaks and valleys. Interestingly, the electric energy density in the piezoelectric elements shows a rich frequency dependent behavior around the electric resonance, whereas, farther below and above it, this quantity only slightly differs among different piezos, and has a smooth behavior, as a function of frequency.

The plots of figures 5 and 6 show how the structure behaves, when the nominal resonance frequency of the shunted piezoelectric resonators is tuned to a structural eigenfrequency. Also here, if the array of tuned piezoelectric resonators were to act as local resonators, or if there where only one piezoelectric element coupled to the structure, the expected response would be the one of a two degrees of freedom (2DOF) system with two resonance peaks and one antiresonance, as shown in [1, 2]. However, the complexity that we have seen emerge from the presence of multiple resonators, tuned at the same nominal frequency, is visible also here. Globally, two resonance peaks at the edge of the frequency range in which the multi-resonator behavior is observed, are given (fig 5).

## 4 CONCLUSIONS and OUTLOOK

The numerical investigations of a structure comprised of multiple, tuned, piezoelectric resonators presented in this work, point to the emergence of phenomena originating from the interaction between mechanically coupled piezoelectric resonators: It appears that in spite of all being electrically identical, the shunted piezoelectric elements display inhomogenous frequency responses among them, as clearly indicated by plots of the electrical energy density for the individual elements. An interpretation for this

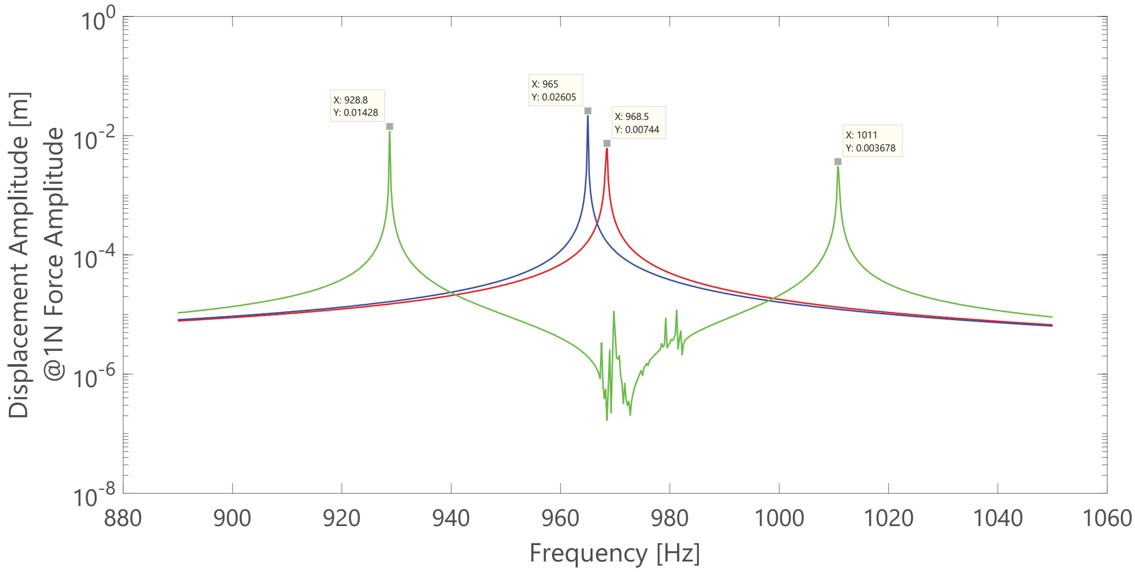


**Figure 5**: Overview of the frequency response (displacement amplitude) of the truss structure under open circuit (red), short circuit (blue) and inductively shunted (green, $L = 210.5H$) conditions, around its first mechanical resonance.

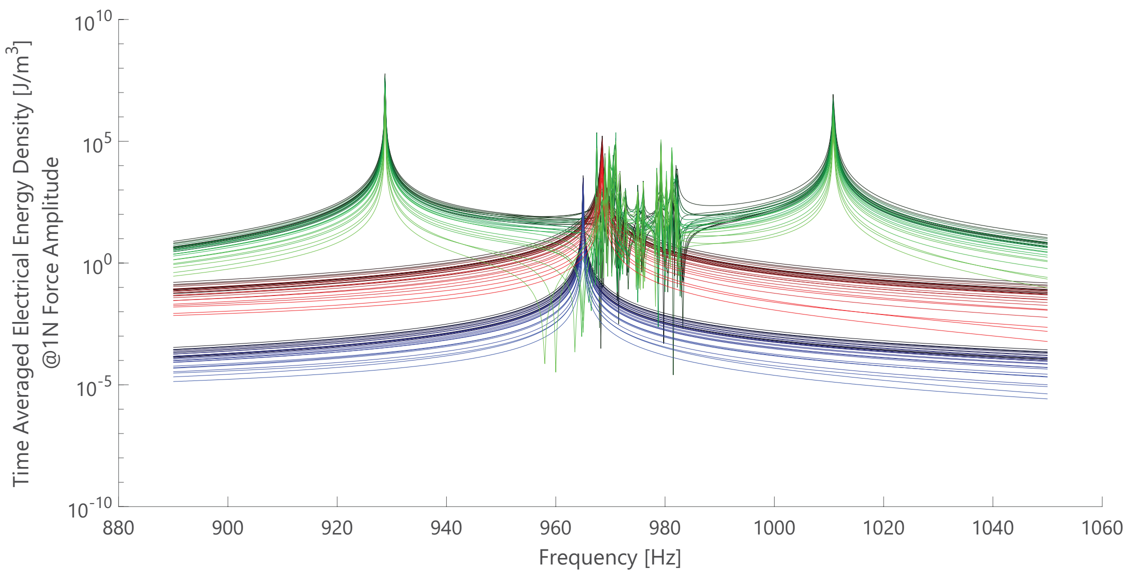


**Figure 6**: Frequency response (time-averaged electrical energy density in the piezo. for each peizo) of the truss structure under open circuit (red), short circuit (blue) and inductively shunted (green, $L = 210.5H$) conditions, around its first mechanical resonance. The shade of the respective color indicates the piezo number the line refers to: black →1, color→, see figure 2 for the piezo numbering scheme

observation can be found in the fact that not only do the mechanical properties of piezoelectric materials depend on the electric boundary conditions, but also the dielectric properties of the material depend on the mechanical boundary conditions. Out of this coupling arise complex interactions between the piezoelectric elements, mediated by the structure that lead to the rich response of the array of mechanically coupled resonators. Thanks to these emergent phenomena, distributed, coupled variable stiffness elements realized via shunted piezos, appear to qualitatively distinguish themselves from discrete piezoelectric treatments. The mechanisms that lead to the interesting dynamic behavior of the described structure will need further investigation.

### 4.1 Experimental verification and challenges

The next challenge of this work will be the experimental verification of these findings. For this purpose a way to properly integrate piezoelectric elements has to be devised. Unlike in the numerical model, the integration in a real setting presents a few practical challenges:

- Piezoelectric elements come in discrete sizes and designs, the structure needs to be designed around the best suitable candidate for the purpose
- To guarantee proper function, thick piezoelectric transducers need to be pre-compressed
- First investigations based on the numerical model appear to indicate that the system is sensitive to material damping and that the described phenomena are most easily observed in a weakly damped system. For this reason the use of conventional polymer based adhesives does not seem to be idea.

The challenges listed above have lead us to design a 'dry mounted' system in which load transfer relies on clamping a ring stack actuator within the diagonal brace. This should allow to meet the requirements we have recognized as relevant so far. However, the realization of a clamped, pre-stressed structure, as the one shown in figure 7, requires high precision components and careful assembly. First experimental results to confirm the findings of the numerical model of the unit cell are expected soon. The preparation of a multi-resonator structure will be tackled once the technique for the preparation of the unit cell will have been refined.

## 5 Acknowledgements

This work was supported by the Air Force Office of Scientific Research grant FA9550-15-1-0397 "Integrated multi-field resonant metamaterials for extreme, low frequency damping."

## References

[1] Forward RL (1979) Electronic damping of vibrations in optical structures. Applied optics 18(5):690–697

[2] Hagood NW, von Flotow A (1991) Damping of structural vibrations with piezoelectric materials and passive electrical networks. Journal of Sound and Vibration 146(2):243–268

[3] Guyomar D, Badel A (2006) Nonlinear semi-passive multimodal vibration damping: An efficient probabilistic approach. Journal of Sound and Vibration 294(1-2):249–268

[4] Delpero T, Bergamini AE, Ermanni P (2013) Identification of electromechanical parameters in piezoelectric shunt damping and loss factor prediction. Journal of intelligent material systems and structures 24(3):287–298

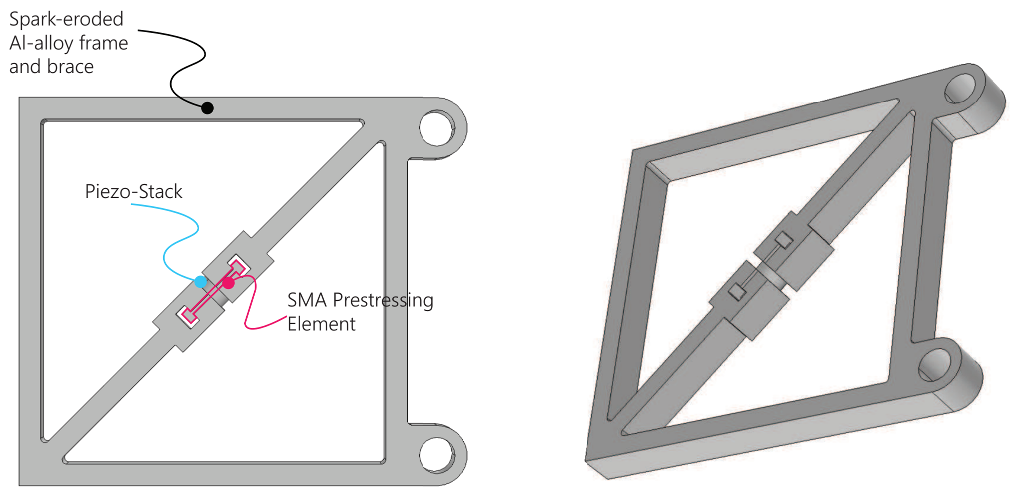


**Figure 7**: Frequency response (time-averaged electrical energy density in the piezo) of the truss structure under open circuit, short circuit and inductively shunted ($L = 210.5H$) conditions, below its first mechanical resonance.


[5] Suzuki S, Yamaguchi T (2019) Panel vibration suppression by using piezoelectric damping system. In: Active and Passive Smart Structures and Integrated Systems XII, International Society for Optics and Photonics, vol 10967, p 1096705

[6] Liu Z, Zhang X, Mao Y, Zhu Y, Yang Z, Chan C, Sheng P (2000) Locally Resonant Sonic Materials. Science 289(5485):1734–1736, DOI 10.1126/science.289.5485.1734, URL http://www.sciencemag.org/cgi/doi/10.1126/science.289.5485.1734

[7] Spadoni A, Ruzzene M, Cunefare K (2009) Vibration and wave propagation control of plates with periodic arrays of shunted piezoelectric patches. Journal of Intelligent Material Systems and Structures 20(8):979–990

[8] Casadei F, Delpero T, Bergamini A, Ermanni P, Ruzzene M (2012) Piezoelectric resonator arrays for tunable acoustic waveguides and metamaterials. Journal of Applied Physics 112:064,902

[9] Krödel S, Delpero T, Bergamini A, Ermanni P, Kochmann DM (2014) 3 d auxetic microlattices with independently controllable acoustic band gaps and quasi-s tatic elastic moduli. Advanced Engineering Materials 16(4):357–363

[10] Wu TT, Huang ZG, Tsai TC, Wu TC (2008) Evidence of complete band gap and resonances in a plate with periodic stubbed surface. Applied Physics Letters 93(11):111,902, DOI 10.1063/1.2970992, URL http://scitation.aip.org/content/aip/journal/apl/93/11/10.1063/1.2970992

[11] Brillouin L (1946) Wave Propagation in Periodic Structures. McGraw-Hill Book Company, Inc.

[12] D'Alessandro L, Belloni E, Ardito R, Corigliano A, Braghin F (2016) Modeling and experimental verification of an ultra-wide bandgap in 3d phononic crystal. Applied Physics Letters 109(22):221,907

[13] Bilal OR, Hussein MI (2011) Ultrawide phononic band gap for combined in-plane and out-of-plane waves. Physical Review E 84(6):065,701

[14] Coffy E, Lavergne T, Addouche M, Euphrasie S, Vairac P, Khelif A (2015) Ultra-wide acoustic band gaps in pillar-based phononic crystal strips. Journal of Applied Physics 118(21):214,902

[15] Bergamini A, Miniaci M, Delpero T, Hannema G, Leibacher I, Zemp A (2019) Shapely atoms. arXiv preprint arXiv:190208763

[16] Bergamini A, Delpero T, Simoni LD, Lillo LD, Ruzzene M, Ermanni P (2014) Phononic crystal with adaptive connectivity. Advanced Materials 26(9):1343–1347

[17] Preumont A, De Marneffe B, Deraemaeker A, Bossens F (2008) The damping of a truss structure with a piezoelectric transducer. Computers & structures 86(3-5):227–239

[18] Jensen JS (2003) Phononic band gaps and vibrations in one- and two-dimensional mass-spring structures. Journal of Sound and Vibration 266:1053–1078, DOI 10.1016/S0022-460X(02)01629-2