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Perspectives on energy harvesting through analogous piezoelectric networks

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Abstract—Piezoelectric coupling to an analogous electrical network has already proven its interest for vibration mitigation. As such a solution optimizes the energy transfers between the electrical and mechanical domains, an extension to energy harvesting is considered.

I. INTRODUCTION

The resonant piezoelectric shunt, made of a resistor, an inductor and a piezoelectric element, is equivalent to a mechanical vibration absorber. When the electrical resonance frequency is tuned to a mechanical resonance, an energy transfer generates a vibration reduction. However, a single resonant shunt is only effective over a narrow frequency band. A broadband solution is still possible by considering an interconnection of piezoelectric patches rather than independent shunts [1]. Furthermore, it has been observed that an optimal multimodal damping can be obtained from the coupling of the considered mechanical structure to its passive electrical analogue [2]. Piezoelectric control solutions using analogous electrical networks have thus been proposed for beams [3] and plates [4].

The aim of the present paper is to synthesize the main results related to multimodal coupling through analogous piezoelectric networks and to raise perspectives related to a possible extension to energy harvesting.

II. MULTIMODAL COUPLING TO ANALOGOUS PIEZOELECTRIC NETWORKS

A. Analogous electrical network

By discretizing the continuous equations describing a mechanical medium, it becomes possible to obtain a set of discrete equations that corresponds to the finite difference model of the structure. Based on an electromechanical analogy, those discrete equations can be represented by an electrical network made of passive components. For example, longitudinal propagation is equivalent to what occurs in a transmission line ruled by the telegrapher's equation. This corresponds to a line of inductors (equivalent to point masses) with connection to the ground through capacitors (equivalent to springs). Analogous networks for bending wave propagation are slightly more complex because they involve transformers that represent the analogues of mechanical levers [2,3]. Such a network is able to reproduce the dynamics of a beam when applying electrical boundary conditions that are analogous to those of the mechanical structure. Coupling a structure to its electrical analogue can be performed through piezoelectric

elements. Those latter take the role of the capacitors in the analogous network. This means that we only need to use magnetic components, such as inductors and transformers, for the interconnection of the piezoelectric elements. The electrical topology is illustrated in FIGURE 1 for the case of a beam and its practical implementation is shown in FIGURE 2. Note that we here consider a periodic layout, meaning that the whole electromechanical structure can be described by a single unit cell. This unit cell is reproduced along one direction to model the electromechanical waveguide. Bending electrical networks have then been extended to a two-dimensional case for the analogue of a thin plate. Such a network has been used for a vibration damping application involving a clamped plate covered with a set of 20 piezoelectric patches [4]. The setup is presented in FIGURE 3, which shows the plate and its analogous electrical network.

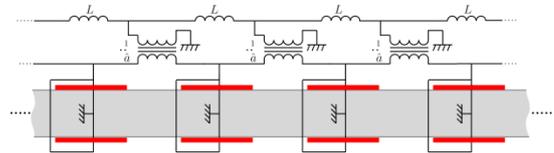


FIGURE 1. ELECTROMECHANICAL PERIODIC WAVEGUIDE

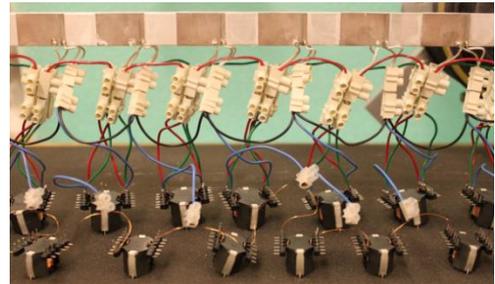


FIGURE 2. BEAM COUPLED TO ITS ANALOGOUS NETWORK



FIGURE 3. PLATE COUPLED TO ITS ANALOGOUS NETWORK

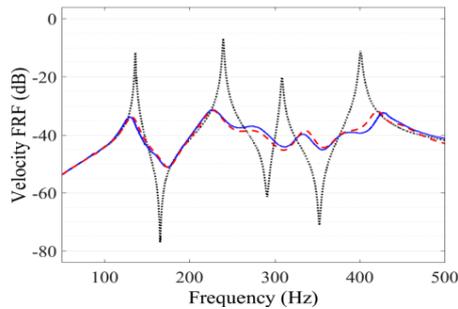


FIGURE 4. FREQUENCY RESPONSE FUNCTIONS WHEN COUPLING A PLATE TO ITS ANALOGOUS ELECTRICAL NETWORK (DOTTED = EXP. WITHOUT NETWORK, SOLID = EXP. WITH NETWORK, DASHED = MODEL WITH NETWORK)

B. Broadband coupling

Coupling a mechanical structure to its analogous electrical network optimizes the energy transfers [1]. This means that the energy can be extracted from the mechanical domain over a broad frequency range. The width of this frequency range depends on the number of electrical unit cells. As long as the discrete approximation of the continuous mechanical structure is valid, the dispersion relations in both domains are approximately the same and the energy transfers are optimized. For vibration damping applications, this corresponds to the synthesis of an electrical network having the same resonant frequencies and the same mode shapes as the ones of the mechanical structure. With this condition, the coupling of the two domains through piezoelectric patches completely modifies the frequency response function of the system as shown in FIGURE 4. Vibration damping is optimized by adding the right amount of resistance into the network. In the end, we obtain a passive solution for vibration mitigation over a broad frequency range.

III. EXTENSION TO ENERGY HARVESTING

A. Reduction of the internal resistance

A first challenge for energy harvesting through an analogous network relies on the minimization of the internal resistance of the magnetic components [5]. Internal resistance is normally not an issue for vibration damping applications because we actually need to extract energy which is then dissipated into heat. However, if we want to turn this amount of energy into useful electrical power, the design of the magnetic components, i.e. the transformers and the inductors, needs to be optimized.

B. Localized or distributed harvesting

Considering an array of interconnected piezoelectric elements raises the question of the positioning of the harvester among the network. Actually, all electrical modes offer nodal lines where no current is flowing through the components. A device capable of extracting electric charges would thus be useless if it is placed around such a nodal line. As a consequence, it is required to quantify the modes involving the highest energy levels in order to place the harvester at a position where the current is maximum. This constraint could be relaxed by using a large amount of distributed harvesters all over the electrical network. Depending on their positioning, they would not be effective over the same frequency ranges but

this would offer a real broadband solution when looking at the global harvested energy that could be transferred into a single storage element.

C. Number of electrical unit cells

A distributed harvesting strategy could potentially involve a very large number of electrical components and conversion devices. However, if we only look at energy transfers generated from a few of the first modes of a mechanical structure, the corresponding analogous network can be limited to a reasonable number of unit cells. Indeed, ten unit cells per wavelength are generally enough. This number of unit cells would allow an adequate analogous coupling up to the third mode of a cantilever beam coupled to a network such as the one in FIGURE 1.

D. Proposed experimental setup

Following the previous considerations, a first setup dedicated to energy harvesting through an analogous piezoelectric network could be made of a cantilever beam covered with a periodic distribution of piezoelectric elements involving 10 electromechanical unit cells. This setup would allow optimal energy transfers up to a frequency around the third mode of the beam. First, a single harvester could be introduced into the analogous network at the end corresponding to the free end of the beam. With this positioning, the harvester is thus far from any node of the first three modes, which allows a simultaneous energy harvesting around the first three resonant frequencies. A second step would then be based on the use of several harvesting devices all over the electrical network but all connected to the same energy storage element.

IV. CONCLUSION

First thoughts have been given to the use of analogous electrical networks for energy harvesting applications. The main results concerning multimodal vibration damping through interconnected arrays of piezoelectric patches have been recalled and we then propose an experimental setup that could be used for an analysis focusing on broadband energy harvesting. Models have already been developed for vibration damping applications and those could be combined with energy harvesting expertise in order to quantify potential benefits offered by analogous piezoelectric networks.

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