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Robin Darleux, Boris Lossouarn, Jean-François Deü. Plate electrical analogue for multimodal energy transfer. 8èmes Journées Nationales sur la Récupération et le Stockage d'Energie, JNRSE 2018, May 2018, Besançon, France. hal-02238860

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***Abstract* — This work presents the implementation of a plate electrical analogue and its validation by comparison between measurements and simulations. We also highlight the possible use of this network as an energy harvester.**

I. INTRODUCTION

Bonding piezoelectric patches on a vibrating structure creates an electromechanical coupling that enables the transfer of the vibration energy to an electrical circuit. The extracted energy can then be either dissipated in a resistive component, or recovered through suitable power electronics. In any case, the design of the electrical circuit has a significant influence on the energy conversion performance. More specifically, piezoelectric shunt damping has been studied to damp one [1] or several [2] modes. These solutions might be effective to extract energy from a few resonances, however the complexity of the electrical circuit increases when considering a large number of modes. Other solutions including interconnected piezoelectric patches coupling the vibrating structure to its electrical analogue have been developed [3,4]. These solutions can help scavenging energy over a wider frequency range but require bonding several piezoelectric transducers on the mechanical structure.

In this paper, we consider a plate as the mechanical structure from which vibration energy should be extracted. Based on a direct electromechanical analogy [5], the unit cell of the electrical network, analog to the unit cell of the mechanical structure, is derived from a discretization of the Kirchhoff-Love theory for plates. A model of the network is developed, in which the electronical damping induced by resistive components is taken into account. The computed currents distribution is then compared to measurements. The comparison validates the fully-passive electrical network that has been realized. Perspectives on further extension to energy harvesting are highlighted as well.

II. MODELING OF A PLATE ELECTRICAL ANALOGUE

A. *Unit cell of the electrical network*

To define the analogous electrical network of a plate, a discrete model of the mechanical structure is derived from a finite difference model of the Kirchhoff-Love equation in harmonic motion. We then use a direct electromechanical analogy [5], which is summed up in TABLE 1. The discrete mechanical equations are then transformed in electrical equations, from which the equivalent unit cell of the analogous electrical network is identified. Complete details are given in [4].

Mechanical quantity	Electrical quantity
Force	Voltage
Velocity	Electrical current
Compliance	Capacitance
Mass	Inductance
Viscous damping	Resistance

TABLE 1. DIRECT ELECTROMECHANICAL ANALOGY

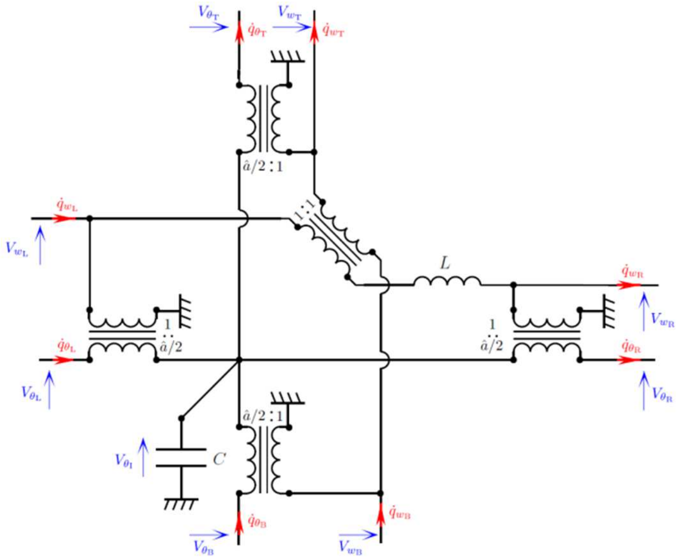

FIGURE 1 : UNIT CELL OF THE ELECTRICAL ANALOGUE OF A PLATE (B. LOSSOUARN ET AL. [4])

The unit cell of the electrical network we obtain is represented in FIGURE 1. The inductance L, the capacitance C and the transformer of ratio 1:1 represent the mass of the mechanical cell, the bending stiffness, and the coupling between the two directions of the mechanical structure, respectively. Transformers of ratio $\hat{a}/2$:1 represent mechanical levers that appear in the finite difference model, where $\hat{a}$ is equivalent to the length of the square cell. Additional components, such as the internal resistances of the inductance L and of the transformer windings, are taken into account as well.

B. *Numerical implantation of the finite difference model*

The unit cell previously defined is reproduced in two orthogonal directions to form the electrical network. Following an assembly process like in the finite element method, the electrical currents and voltages that appear in FIGURE 1 are then calculated in the case of external voltages applied at nodes of the network. The frequency response function (FRF) of the voltage drop across the inductors L is computed, and will be compared to experimental results in the next section.

III. MEASUREMENTS ON A FULLY-PASSIVE PLATE ELECTRICAL ANALOGUE

A. Experimental setup

A fully passive network has been realized and is shown in FIGURE 3. Inductive components have been made following the method proposed in [6] and piezoelectric capacitances have been replaced by ceramic capacitors. A voltage excitation induces an electrical current distribution through the network. Those currents are measured by a differential voltage measurement across the inductors.

B. FRFs and currents distribution in the network

The FRF of the current flowing through the inductors divided by the excitation voltage amplitude has been measured at all 42 centers of the unit cells of the network. A comparison of the results obtained by simulation and measurements at one specific unit cell is shown in FIGURE 3. The measured operational current modes shapes, which mimic the vibration modes of the mechanical structure such as in FIGURE 4, can be compared to numerical results as well. These comparisons validate the electrical network, which has been developed as an electrical analogue of a mechanical plate.

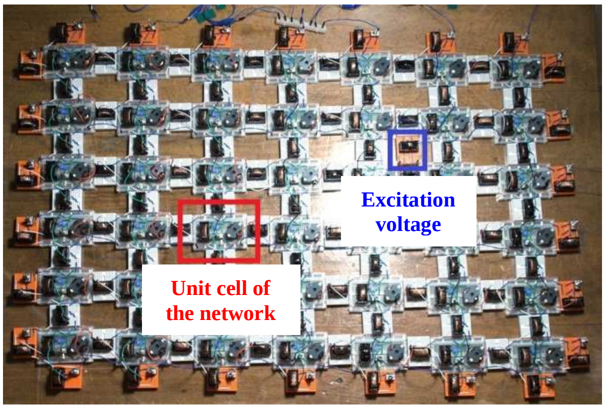

FIGURE 2. ELECTRICAL NETWORK ANALOGOUS TO A SIMPLY SUPPORTED PLATE. THE NETWORK IS MADE OF 6X7 IDENTICAL UNIT CELLS.

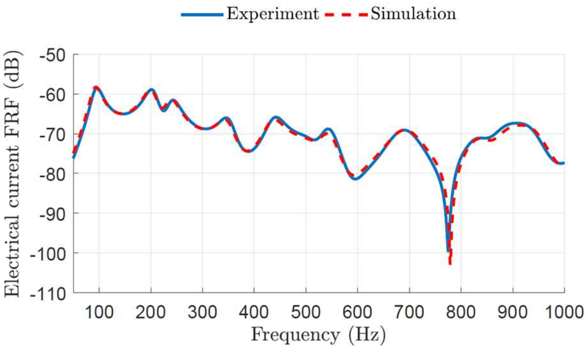

FIGURE 3. COMPARISON BETWEEN EXPERIMENTS AND SIMULATIONS OF THE CURRENT FRF IN THE ELECTRICAL NETWORK

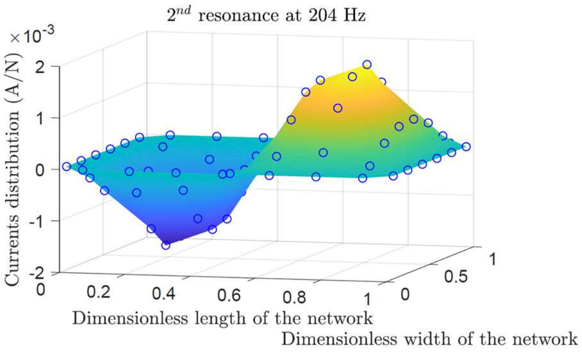

FIGURE 4. ELECTRICAL CURRENT DISTRIBUTION IN THE ELECTRICAL NETWORK NEAR THE SECOND RESONANCE

IV. CONCLUSION

In this work, a plate electrical analogue dedicated to multimodal energy transfer is proposed. The analogue network is designed by discretizing the Kirchhoff-Love theory equations and using a direct electromechanical analogy. The unit cell we obtain is periodically repeated to create the network. Simulations and measurements of the currents distribution across the inductors of the network validate the concept of a plate electrical analogue.

Now validated, the network would be able to extract vibration energy from the considered plate over a frequency range of nearly 1 kHz that includes 10 modes. The connection to the vibrating structure will be done thanks to piezoelectric patches, first for a broadband vibration damping purpose, and then for an energy harvesting purpose. As it stands, the main limitation to develop a piezoelectric energy harvester with such an electrical analogous network is that the inductors and transformers of the network are too resistive. The ensuing energy dissipation leads to damped resonances (see FIGURE 3), which limits the energy that could be recovered. The electrical components should thus be optimized as to reduce the internal resistances of the network, and so enable scavenging of the energy transferred from the mechanical structure.

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