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System-level parameter estimation of magnetoelectric transducers for wireless power transfer

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***Abstract*—This paper presents a system-level electromechanical model of a magnetoelectric transducer for wireless power transfer. Based on a single-degree-of-freedom (SDOF) model, we estimate the equivalent parameters of a lumped-mass model. Impedance measurements at several actuation levels allow us to quantify the evolution of the main parameters of interest and the figure of merit (FOM) for the future optimization of the electrical interface between the transducer and the circuit to supply.**

Keywords: magnetoelectric transducers, wireless power transfer, single-degree-of-freedom model (SDOF), admittance measurements.

I. INTRODUCTION

Magnetoelectric (ME) transducers have proven to be a good candidate to power an embedded biomedical device wirelessly [1,2]. These composite materials use a magnetostrictive (MS) layer - to transform a magnetic energy into a mechanical motion – bonded to a piezoelectric layer, which create the electric energy. An optimization of the electrical interface between the transducer and the load (either an electrical circuit or a battery) is then required. Though very useful when optimizing the ME transducer itself, elaborate finite-element models [3] are hard to use when trying to optimize the power transfer from an electromagnetic source to an electrical load because of their computational complexity. For that reason, very few works have studied how realistic electrical interfaces [4,5,6] affect the power transfer of ME transducers. To that purpose, system-level models are required.

In this paper, we focus on the system-level electromechanical parameters of a ME transducer in the absence of an electromagnetic field. We show how the addition of a MS layer to a piezoelectric resonator modifies the quality factor and the coupling coefficient of the generator and, all in all, the figure-of-merit that one must optimize to design the power transfer interface.

II. MODEL OF AN ELECTROMECHANICAL TRANSDUCER

Even though piezoelectric elements sometimes exhibit nonlinear behaviors [7], they are usually modelled as a coupled single-degree-of-freedom mechanical resonator, when operated at low levels close to one of their resonance frequencies. Such a model (see Figure 1) is made of an effective mass M suspended by a spring of stiffness K. The factor α (N.V^{-1}) accounts for the bidirectional coupling between the mechanical and the electrical domains. The capacitor C_p represents the capacitance of the piezoelectric element. The damper c models the mechanical losses of the system.

In the absence of a magnetic field, we assume that the model of a single-degree electromechanical resonator (Figure 1) remains valid when the MS layer is bonded to the piezoelectric element.

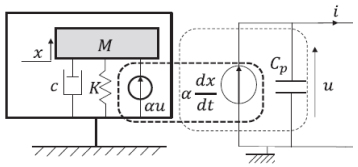


FIGURE 1. ELECTROMECHANICAL MODEL OF A LINEAR ELECTROMECHANICAL RESONATOR.

The MS layer is supposed to modify the equivalent coefficients M, K, c, α and C_p. The validity of this assumption will be verified in section III. The equations governing the systems behavior are the following:

$$\begin{cases} M\dfrac{d^2x}{dt^2} + c\dfrac{dx}{dt} + Kx + \alpha u = 0 \\ i = \alpha\dfrac{dx}{dt} - C_p\dfrac{du}{dt} \end{cases} \quad (1)$$

For the study, we also define the quality factor $Q = M\omega_0/c$ and the modified electromechanical coupling coefficient $k_m^2 = \alpha^2/KC_p$. The natural (short-circuit) angular frequency is written $\omega_0 = \sqrt{K/M}$. Based on this model, a parameter identification procedure can be performed.

III. EXPERIMENTAL VALIDATION OF THE MODEL

A. Experimental setup

Our first sample is composed of a 7mm-width PZT-5H piezoelectric plate which is put into oscillation in the in-plane direction by applying a voltage with an impedance analyzer. A frequency sweep is performed close to its resonance frequency. Similar measurements are then performed on the same sample after gluing a MS layer (Terfenol-D) with insulating epoxy glue. A picture of the composite transducer obtained after the bonding process is reported in Figure 2. In the following paragraphs, the piezoelectric sample will be denoted “P” and “P-T” will be the magnetoelectric composite obtained with the Terfenol D.

The measurements were taken using a sample holder prototype fabricated with a 3D printer (see Figure 3). Apart from the electrical contacts, the whole holder prototype is made of plastic to avoid the use of electromagnetic-sensitive materials for future applications in medical implants. All the measurements were taken with an HP 4194A impedance analyzer.

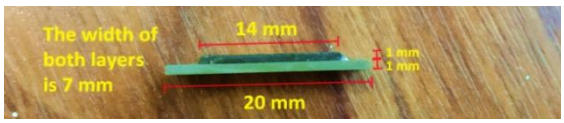


FIGURE 2. P-T SAMPLE: MAGNETOELECTRIC COMPOSITE TRANSDUCER (LIGHT GREEN : PIEZOELECTRIC LAYER - DARCK: MAGNETOSTRICTIVE LAYER)

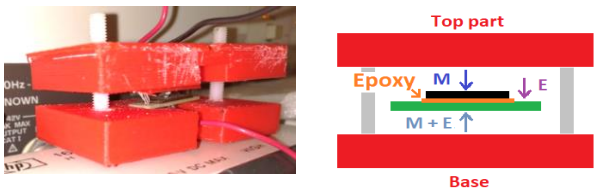


FIGURE 3. THE SAMPLE HOLDER (LEFT: PICTURE, RIGHT: SCHEMATIC) "M" DENOTES A MECHANICAL CONTACT AND "E" AN ELECTRICAL CONTACT.

B. Experimental results

1) Model validation

Admittance curves measured on the "P sample" and "P-T sample" are reported in Figure 4. For both samples, the linear SDOF model fits very well with the measurements, for each actuation level.

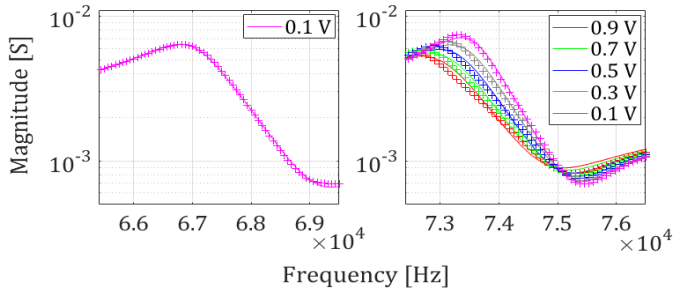


FIGURE 4. ADMITTANCE MEASUREMENTS AND FIT FOR THE "P SAMPLE" (LEFT) AND "P-T SAMPLE"(RIGHT) FOR DIFFERENT ACTUATION LEVELS.

2) Equivalent electromecanical parameters

Based on the admittance measurements of section B.1, we report, in Figure 5, the parameters obtained at different actuation voltages. As one can expect from a linear model, all the parameters estimated on the P-sample are constant. On the contrary, significant variations of the estimated parameters are observed on the P-T sample. The addition of a MS layer strongly impacts the electromechanical behavior. The results show clearly that, on the P-T sample, all the parameters are function of the voltage level. In particular, the quality factor of the P-T sample decreases by around 50% between 0.1V and 1V.

One of the most important characteristic when trying to optimize a power transfer system is the figure-of-merit (FOM) $k_m^2 Q$ (see Figure 6). Due to the sharp decrease of the quality factor, the FOM of the P-T composite also decreases strongly (28%).

IV. CONCLUSION

In this paper, we have estimated system-level parameters of a ME transducer for wireless power transfer. Contrary to the piezoelectric element alone, we have shown that the coupling coefficient and the quality factor of the composite strongly depend on the voltage. In particular, the quality factor of the composite decreases sharply with the voltage level (more than 50% between 0.1V and 1V) which has a strong consequence of the figure-of-merit $k_m^2 Q$.

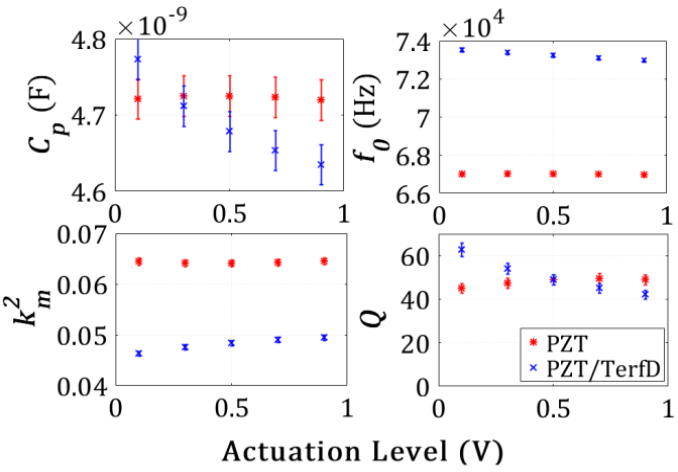


FIGURE 5. PARAMETERS ESTIMATED FROM THE ELECTROMECHANICAL MODEL

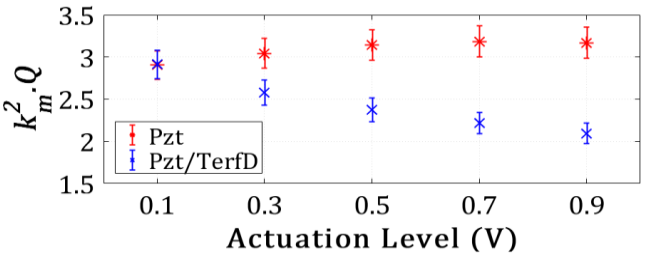


FIGURE 6. EVOLUTION OF THE FOM.

The origin of such a variation is still unsure but it may be related to losses such as eddy currents in the MS layer. System-level conclusions can readily be used for the design of an optimized electrical interface for power transfer. Further work will aim at quantifying the impact of adding an electromagnetic field on the overall behavior.

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