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# Highly-coupled PZT-based vibration energy harvester for broadband applications

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**Abstract**— This paper reports on the design and experiment of a highly-coupled piezoelectric energy harvester. Such a device is necessary to benefit from non-linear electrical techniques to improve the frequency bandwidth. A previously developed 2-degree of freedom (2-DOF) analytical model is improved with the Rayleigh method and is used to understand electromechanical interactions and for a preliminary design. As a result, we built a PZT-5A cantilever embedding a long proof mass. The tests demonstrate a strong electromechanical coupling coefficient ( $k^2=10.2\%$  for the 1<sup>st</sup> mode), which represents  $k^2/k_{31}^2 = 67\%$  of the material coupling.

## I. INTRODUCTION

Highly coupled generators are a relevant solution for broadband vibration harvesting. When associated with electrical methods that influence the mechanical resonator dynamics, their harvesting bandwidth can be enlarged thanks to the strong electromechanical coupling of the system [1-2]. Thus, harvesters embedding single crystals have been designed in order to maximize the global coupling. In a previous work [3], we explained the benefits of long proof mass systems to homogenize the strain distribution in the piezoelectric material. We also presented a PMN-PT prototype exhibiting a global electromechanical coupling coefficient  $k^2 = 17\%$ .

Here, we propose to take benefit of long proof mass systems to design a highly coupled PZT-5A based cantilever. This material is widely used for energy harvesting as it has a high Curie temperature ( $T_c^\circ = 360^\circ\text{C}$ ) and a lower cost than single crystal materials [4].

In section II, we present the Rayleigh method applied on the mode shape computed from the 2 degree of freedom (2-DOF) model presented in [3]. A design methodology is described in section III and the modelling, simulations and measurement results are presented and compared in section IV.

## II. ANALYTICAL MODEL

The studied system is a bimorph piezoelectric cantilever whose electrodes are connected in parallel as shown in FIGURE 1. We firstly neglect the beam mass, as for the 2-DOF model presented in [3]. We consider the proof mass  $M_t$  as well as its rotary inertia  $I_t$  and the distance  $D_t$  of its center of gravity with the end of the bending beam.

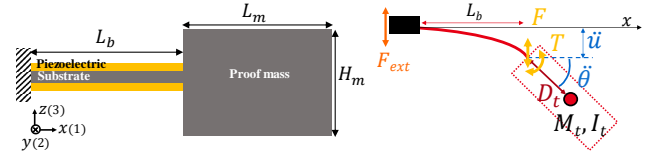


FIGURE 1 : CLAMPED-FREE BEAM SYSTEM ON THE LEFT AND BEAM DURING BENDING ON THE RIGHT

Thereafter, we propose to take the kinetic influence of the beam mass into account thanks to the Rayleigh Method. This method has been extensively detailed for long proof mass systems in [5] where the mode shape were determined with the continuous beam model. By considering energy conversion law, we deduce a single degree of freedom system for each resonant mode:

$$\begin{cases} M_j \ddot{r} + K_j r - \Theta_j v = -B_{f_j} \ddot{w}_B \\ \Theta_j \dot{r} + C_p \dot{v} + i = 0 \end{cases} \quad (1)$$

Where  $M_j$ ,  $K_j$ ,  $\Theta_j$ ,  $B_{f_j}$  and  $C_p$  are the equivalent inertial mass, stiffness, coupling term, forcing vector and clamped capacitance respectively.  $\ddot{w}_B$  is the base acceleration,  $v$  is the voltage across the electrodes and  $i$  is the current flowing through the electrodes.  $r$  denotes the displacement at the beam end, while the subscript  $j \in [1, N]$  represents the resonant mode of interest.

By considering the mode shapes given by the 2-DOF model, we can analytically express the system coefficients (1) as well as the resonant frequencies and coupling for both first and second flexural resonant modes. This simplifies both the understanding of the electromechanical interactions and the design.

For instance, we can prove that the proof mass density does not affect the global coupling once the proof mass is much heavier than the beam. Only the proof mass shape has an influence on the strain distribution. Furthermore, to increase the first mode electromechanical coupling, it can be shown that the rotary inertia to mass ratio  $I_t/M_t$  and the distance  $D_t$  should be maximized.

## III. DESIGN PROPOSITION

The proposed methodology consists in designing a cantilever offering the same expected power as the prototype presented in [3] and the best possible coupling for the first resonant mode. We expect the quality factor to be the same for both systems. The PZT-5A from Noliac company is selected

(Table 1) and we use steel as the substrate and proof mass material.

TABLE 1: MATERIAL COEFFICIENTS FROM NOLIAQ NCE51 (PZT-5A)

| $d_{31}$                | $S_{11}^E$                            | $\epsilon_{33}^T$      | $k_{31}^2$ |
|-------------------------|---------------------------------------|------------------------|------------|
| -208 pm.V <sup>-1</sup> | $17 \times 10^{-12}$ Pa <sup>-1</sup> | 1900 F.m <sup>-1</sup> | 15.13%     |

Optimal geometrical parameters have been determined thanks to the proposed 2D model with plane stress assumption and 3D FEM simulations were performed for an accurate estimation of the theoretical electromechanical coefficient. The system has been assembled with epoxy glue (FIGURE 2). The substrate and PZT patches thicknesses are equal to 0.4mm and 0.3mm respectively. We performed admittance measurement to experimentally determine the system parameters (FIGURE 3).

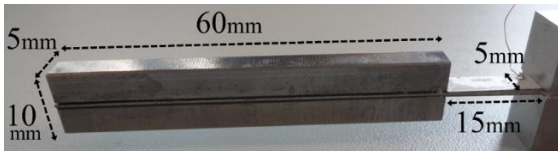


FIGURE 2 : PROTOTYPE WITH PZT-5A

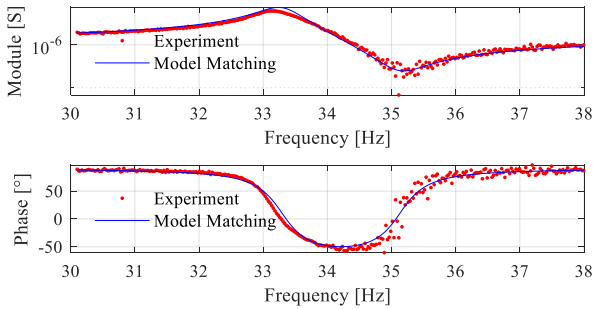


FIGURE 3 : MEASURED ADMITTANCE OF THE PROTOTYPE AND MATCHING WITH THE MODEL PRESENTED IN [1].

#### IV. DISCUSSIONS

The assembled prototype shows a large electromechanical coupling coefficient ( $k^2 = 10.2\%$ ) which is, as far as we know, the best value obtained for a vibration energy harvester made with PZT-5A material. The quality factor  $Q_m$  and the figure of merit  $k_e^2 Q_m = k^2 Q_m / (1 - k^2)$  are equal to 50 and 5.6 respectively.

We can notice a difference between the simulation and modelling results (Table 2). Since the length-to-width ratio of the beam is equal to 3, neither plane stress nor plane strain assumption are fully respected for our cantilever. Even though experimental results seem close to our 2D analytical model, this cannot prove an exact validation of beam modelling. When we take the imperfectly clamped end and the glue into account in 3D simulations, the resulting global electromechanical coupling coefficient  $k^2$  decreases. This is explained by losses of elastic energy in non-piezoelectric material. As an example, we reach a coupling of 10.5% if we consider that the piezoelectric patches are at a distance of 50 $\mu$ m from the clamped-end block and the proof mass and if the glue thickness is equal to 5 $\mu$ m (the epoxy Young modulus is estimated to be 4GPa).

On the one hand, the relatively high width-to-length ratio and the clamping end effect on lateral strain artificially increase the coupling between model and simulations. On the other hand, the fabrication process decreases the coupling between simulations and experiment. As a result, a model fitting the experimental data cannot guarantee the model validation and can be explained by a combination of several errors that vanish. The 2D model is however a relevant tool for the design of highly coupled generators. 3D FEM including glue thicknesses and unperfected clamping must be used to have a good performance prediction.

TABLE 2: COUPLING AND RESONANT FREQUENCY OBTAINED WITH THE MODEL, 3D FEM AND EXPERIMENT

|   | $f_{sc}$ | $k^2$ |
|---|----------|-------|
| Proposed modelling                      | 34.2 Hz  | 11.8% |
| 3D FEM with perfect clamping            | 34.8 Hz  | 14.2% |
| 3D FEM with glue and imperfect clamping | 30.8 Hz  | 10.5% |
| Experiment                              | 33.3 Hz  | 10.2% |

#### V. CONCLUSION

In this paper, we propose a design methodology in order to maximize the coupling of linear piezoelectric energy harvesters. The proposed methodology, based on the resolution of a 2DOF model coupled with the Rayleigh method and 3D simulations, is applied to design PZT-5A-based energy harvester. We have been able to obtain experimentally a coupling of 10.2%, which represents  $k^2/k_{31}^2 = 67\%$  of the material coupling. Differences between model, simulations and experiment are explained by the influence of the clamped-end imperfections and the glue.

Future work will focus on improving the fabrication and the understanding of the clamping condition influence.

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