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# Load resistance impact on the electromechanical dynamic of bistable piezoelectric energy harvesters

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**Abstract**—Bistable piezoelectric energy harvesters are prominent solutions in the field of vibration energy harvesting due to their broadband behavior. However, the impact of the electrical interface and especially the load impedance needs to be addressed. In this paper, the impact of the load resistance on the electromechanical dynamic of the harvester has been studied. Experimental tests allowed us to demonstrate that the load resistance induces an electrical damping allowing to tune the bandwidth of the harvester as well as the harvested power. The results presented in this paper should be considered for the future development of harvested power optimization algorithms as well as orbit jump strategies.

## I. INTRODUCTION

During the last decades, there has been a growing interest for new energy harvesting solutions that could enable the development of battery-less sensor nodes. Piezoelectric energy harvesters (PEH) are of particular interest because of their high energy density and their integration capability. The dynamic of PEH can be modelled by a simple set of differential equations according to [1]. Since the piezoelectric energy harvester exhibits a bidirectional electromechanical coupling, it has been proven that the electrical interface has a certain impact on the behavior of the system.

Previous works focused on the load resistance impact on the bandwidth for linear piezoelectric energy harvesters [2] and non-linear monostable piezoelectric energy harvesters [3]. The works presented in [4] focused on the load resistance optimization in order to maximize the harvested power for bistable PEH. However, to date, there is no experimental analysis of the impact of the load resistance on bistable PEH.

In this paper, we propose an experimental study of the load resistance impact on the harvested power as well as on the bandwidth of the bistable PEH. First, we present the experimental testbench. In a second time, the experimental protocol is presented. The experimental measurements are finally discussed.

## II. EXPERIMENTAL TESTBENCH

In this paper, we focus on a bistable PEH made of an inertial mass connected to two parallel buckled beams. The beams are clamped on one side and connected to an amplified piezoelectric actuator (APA) on the other side as depicted in Fig. 1. The APA is built around a stack of lead titanate-zirconate piezoelectric ceramic (PZT) installed in a metallic shell.

An experimental testbench, depicted in Fig. 2, including a dSpace real time interface, an electromagnetic shaker and its associated power amplifier, a differential laser vibrometer and

a programmable decade box as been set up. The PEH depicted in Fig. 1 is fixed to the shaker. In order to measure the acceleration amplitude of the excitation signal, an accelerometer is also fixed to the shaker. The dSpace interface is controlled through Matlab scripts and sends control signals to the decade box and the power amplifier driving the shaker. A differential laser vibrometer is used to measure the displacement and speed of the mass of the electromechanical harvester. The piezoelectric voltage is transferred to the dSpace interface by mean of a voltage follower in order to isolate the PEH from the dSpace interface input impedance.

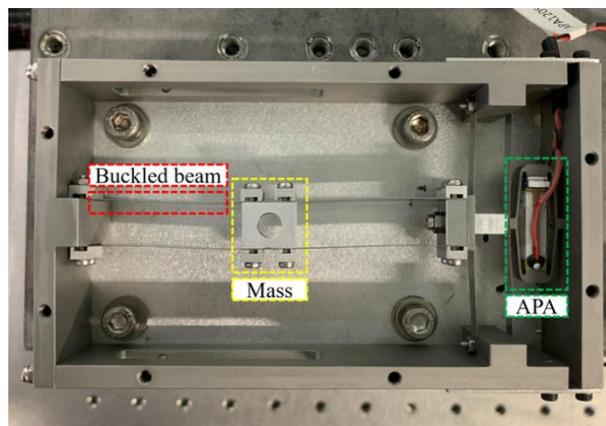


FIGURE 1. BISTABLE PIEZOELECTRIC ENERGY HARVESTER

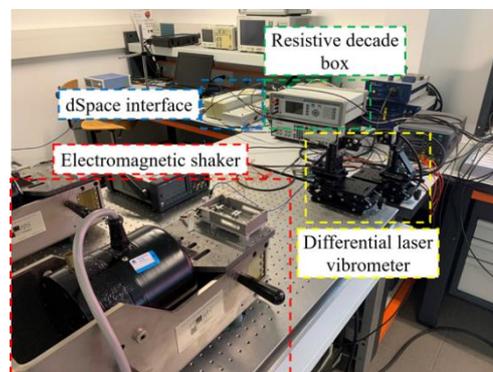


FIGURE 2. EXPERIMENTAL TESTBENCH

## III. EXPERIMENTAL PROTOCOL

Bistable PEH might exhibit two types of motion: intra-well and inter-well motions. Intra-well motion consists in small

oscillations of the inertial mass around one of the two stable positions whereas inter-well motion consists in oscillations around the two stable positions. The experimental characterization is performed on the inter-well motion also known as high-energy orbit. The PEH is submitted to a sinusoidal acceleration of amplitude  $\gamma_m = 5 \text{ m.s}^{-2}$  and the vibration frequency is swept from 30 Hz to 120 Hz. In order to force the inter-well motion operation of the energy harvester, an orbit jump sequence has been developed. The acceleration amplitude is progressively increased up to  $17 \text{ m.s}^{-2}$ . Under such large vibration amplitude, the PEH starts operating in inter-well motion. Finally, the acceleration amplitude is slowly brought back to  $\gamma_m = 5 \text{ m.s}^{-2}$  so that the PEH remains in inter-well operation even though the acceleration amplitude is smaller.

The aforementioned orbit jump sequence and frequency sweep are performed for 70 load resistances (from 100  $\Omega$  to 30 k $\Omega$ ). The voltage, displacement, speed and acceleration waveforms are stored for each combination of resistance and vibration frequency.

#### IV. RESULTS AND DISCUSSION

Fig. 3 illustrates the impact of the load resistance on the dynamic of the bistable PEH. It can be seen that the cut-off frequency of inter-well motion  $f_c$  is a function of the resistance. For small resistance values ( $R < 200 \Omega$ ) or large resistance values ( $R > 20 \text{ k}\Omega$ ), this cut-off frequency is close to 70 Hz. However, we can observe that  $f_c$  decreases until it reaches a minimum of 50 Hz when the resistance is close to 1409  $\Omega$ .

Indeed, this resistance is equal to  $R = \frac{1}{2c_p\omega}$  (with  $C_p$  being the capacitance of the piezoelectric material and  $\omega$  the angular frequency of the vibration) which maximizes the electrical damping.  $f_c$  decreases with the damping which explains that the PEH with a resistance value close to 1409  $\Omega$  exhibits a relatively low cut-off frequency whereas a PEH connected to a low damping resistance (e.g. 100  $\Omega$  or 30 k $\Omega$ ) exhibits a relatively high cut-off frequency (70 Hz).

The harvested power depends on the electrical damping associated to the resistance value. We can observe that the harvested power reaches two maxima for two resistances ( $R = 1012 \Omega$  and  $R = 2964 \Omega$ ). These two resistances allow to reach an electrical damping equal to the mechanical damping, thus maximizing the harvested power. If the resistance is close to 1409  $\Omega$ , the electrical damping is greater than the mechanical damping. The system is therefore overdamped and the harvested power slightly decreases. Conversely, if the resistance is larger than 2964  $\Omega$  or smaller than 1012  $\Omega$ , the electrical damping is lower than the mechanical damping which explains that the harvested power also decreases.

These experimental results prove that it is possible to adjust the harvested power and the critical angular frequency by tuning the load resistance. If the resistance is finely tuned for each vibration frequency, it is possible to harvest more than 1 mW over a frequency band from 30 Hz to 70 Hz as illustrated in Fig. 4. This result demonstrates the wideband behavior of the bistable harvester as well as the interest for designing adaptive electrical interfaces for which the input impedance is dynamically optimized as a function of the vibration.

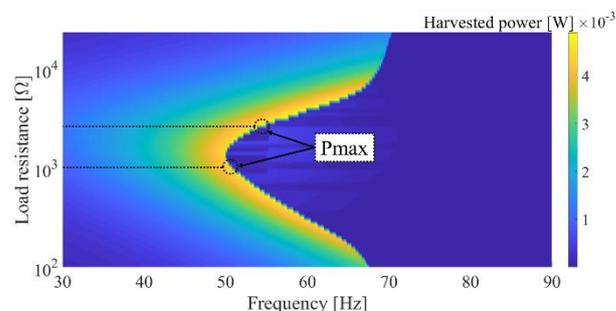


FIGURE 3. HARVESTED POWER AS A FUNCTION OF THE FREQUENCY AND THE LOAD RESISTANCE

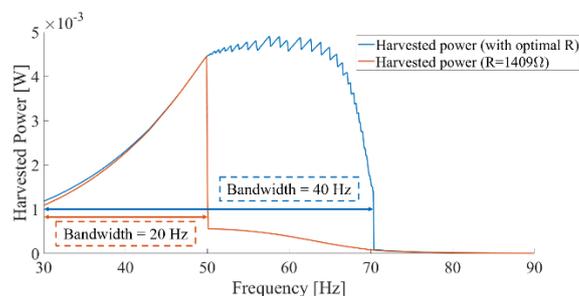


FIGURE 4. MAXIMUM HARVESTED POWER AS A FUNCTION OF THE FREQUENCY

#### V. CONCLUSION

In this paper, we presented the impact of the load resistance on the dynamic of the bistable piezoelectric energy harvester for the high-energy orbit. We experimentally proved that the optimal electrical damping which maximizes the harvested power is associated to a load resistance. Moreover, we showed that it is possible to tune the electrical damping of the system by tuning the load resistance, thus optimizing the bandwidth and the harvested power. Considering the presented results, a maximum power point tracking algorithm and an orbit jump strategy aimed at fully exploiting the potential of bistable PEH will be developed and implemented.

#### ACKNOWLEDGMENT

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