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Modelling and experimental verification of more efficient power harvesting by coupled piezoelectric cantilevers

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Abstract. A new piezoelectric energy harvester design is proposed in order to achieve a wider bandwidth without compromising energy conversion efficiency. By coupling two cantilevers where the tip of the bottom one is attached to the base of the upper one, the simulated harvester will have a wider bandwidth and higher power output compared with two simulated single tuned single cantilevers. This is a compact design, using only half the area compared to two parallel single cantilevers at the price of a small increase in height. The measured coupled harvester has approximately 1.7 times higher energy output than the combination of two measured tuned single cantilevers achieved by a coupling with less mechanical damping. With an improved coupling the power output is increased to 2.3 times higher than two single tuned cantilevers.

1. Introduction

Harvesting energy with piezoelectric cantilevers utilizing ambient vibrations is environmental friendly, since it replaces batteries. Battery-free operation enables new applications to be incorporated in harsh environments such as gas turbines [1].

A single piezoelectric cantilever has a narrow range of resonance frequencies where it effectively can convert vibrations to electricity. To widen this range of effective harvestable resonance frequencies, without losing power output, is a very important challenge when developing new designs [2]. Over the recent years of research many new approaches have been reported on how to widen the bandwidth with little or no loss of power output. Li et al (2014) proposed an array of structures with a different resonant frequency for each structure [3]. Soliman et al (2008) used an amplitude limiter to gain broader bandwidth [4]. Petropoulos et al (2004) used coupled oscillators [5]; Spreemann et al (2006) used magnets to achieve a nonlinear harvester resulting in broader bandwidth [6]. Ramlan et al (2012) tested bi-stable structures [7], and Zhu et al (2010) used a large inertial mass (large device size) with a high degree of damping [2]. Another way to increase the power output and the bandwidth has been suggested by Zhou et al (2011) where a primary beam was used as a multimode magnifier [8]. In this design the secondary beam multi-mode energy harvester is attached to the primary beam multimode dynamic magnifier and this design has a broader bandwidth and the harvested energy is greatly increased. To further enhance this effect Wu et al (2012) describe a two degrees of freedom

(2DOF) piezoelectric energy harvester [9], where the secondary beam is cut inside the main beam. This makes the design less bulky, results in a broader bandwidth with two closely spaced peaks, and gives a high power output from both beams.

The presented and developed harvester in this paper uses commercial components and is a 2DOF where one cantilever acts like a magnifier and by the design is also magnified by the other cantilever. This design enhances the power output and gives a wider bandwidth than an array of two tuned single cantilevers. The design gives a small increase in volume but utilizes the bottom beam more efficiently for higher energy output, much due to the improved and extended strain profile of this beam.

2. Design

The design attaches a MIDE v22b cantilever on top of a MIDE v21b cantilever (both commercially available from MIDE) with the v22b cantilever folded backwards (Figure 1) over the bottom MIDE v21b that is clamped between two alumina bars. By using this design the bottom cantilever will act as if attached on both ends and the bottom cantilever will magnify the top cantilever movement. Hence the harvester will deliver a higher power output.

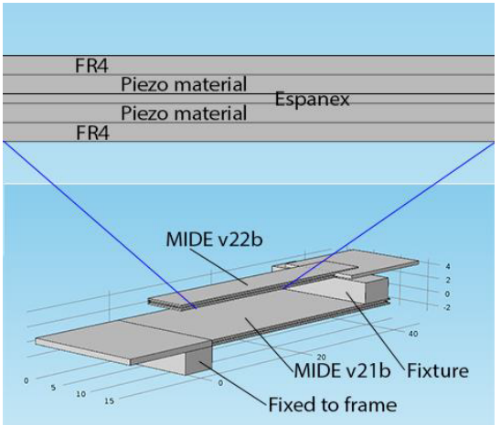

Figure 1. The coupled model in COMSOL Multiphysics.

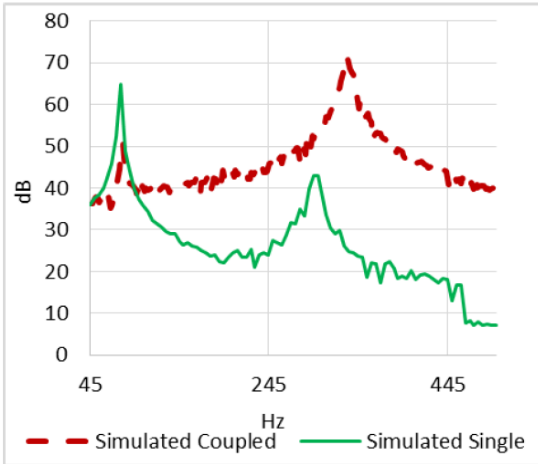

Figure 2. Red dotted line is the simulated couple harvester vs the green line is the two single cantilevers, compared by power output by voltage square and the simulated couple harvester has 10.5 times higher energy output.

3. Simulation

An extension to the single cantilever theory has to be applied in order to describe two connected beams as a couple for enhanced energy output. W. Zhou et al (2011) [8] extend the single cantilever theory to cover two coupled beams with a multi-mode design. This design is proved to yield a higher energy output and to broaden the bandwidth.

Our modification of their design uses two piezoelectric cantilevers folded over each other (Figure 1) instead of extending in the same plane. This design will be able to harvest from both cantilevers with an extra voltage output for the bottom cantilever originating from the top cantilever where the coupling will act more like an attachment for the bottom cantilever. This design is realized with industrial components and will consume only half the area compared to two single cantilevers. The height is slightly increased but in total the design provides an appropriately manageable harvester.

A model of a single MIDE v21b cantilever [10] is built within COMSOL Multiphysics. The real MIDE v21b is a biomorph piezoelectric cantilever with five layers (figure 1): FR4, Piezo material (PZT), Espanex, Piezo material and FR4 [11]. The length and width for the layers are measured with calipers and the thicknesses of the layers are measured with a microscope (table 1) as these were not available in the specification. The length, width and thickness are carefully calibrated so that the cantilever has the resonance frequency 274 Hz in COMSOL, which is the specified resonance frequency without tuning weight given by MIDE [10]. With the tuned single cantilever (v21b) as starting point another top cantilever (v22b) is attached at the free moving tip of the first (bottom) one, so that the top one extends out over the bottom one (figure 1). For comparison, two single harvesters were tuned so that each one showed resonance at one of the two resonance frequencies of the coupled harvester. The voltage responses as a function of frequency for the two differently tuned cantilevers were then added together.

Material properties	Young's modulus (E_p, Pa)	Piezoelectric constant (d_{31}, m V^{-1})	Dielectric constant (ε_{33}, F m^{-1})	Density (ρ, K m^{-3})	Poisson's ratio	L × w × t (mm × mm × mm)
PZT	63×10^9	-190×10^{-12}	830×10^{-10}	7800	0.3	36 × 15.2 × 0.18
FR4	22×10^9	-	-	1920	0.28	36.5 × 17 × 0.18
Espanex	3.2×10^9	-	-	1300	0.34	36 × 17 × 0.09
Damping material	3.5×10^5	-	-	-	0.28	5 × 17 × 0.01

Table 1, materials and constants used in the simulation for the MIDE v21b cantilever.

4. Result

A single v21b cantilever and a single v22b cantilever are simulated from 40-500 Hz. The voltage outputs are added together. The coupled model is also simulated from 40-500 Hz. The voltage output is converted to power by voltage square and the simulation result is compared (Figure 2) and the couple harvester shows a 10.5 times higher power output integrated over frequency band 40 - 500 Hz.

The prototype I is assembled by a bottom v21b cantilever, attached by two aluminum clamps. The coupling to the top v21b is also of aluminum and has a weight of 3.5 g (Figure 3). The protecting plastic and contact plastic protections are removed to reduce weight from the top v22b. The measured power output for the double single harvester is compared with the measured energy output for the coupled harvester (Figure 4), where the measured coupled harvester has 1.7 times higher energy output. To gain a higher power output, as predicted by the simulations, the coupling fixture between v21b and v22b has to be reduced in weight.

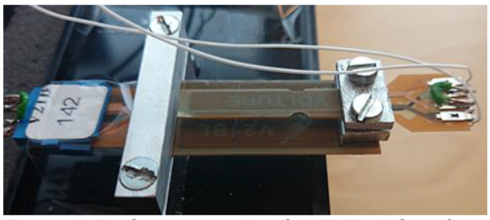

Figure 3. Built prototype I with MIDE v21b at the bottom, the coupling fixture and the MIDE v22b at the top.

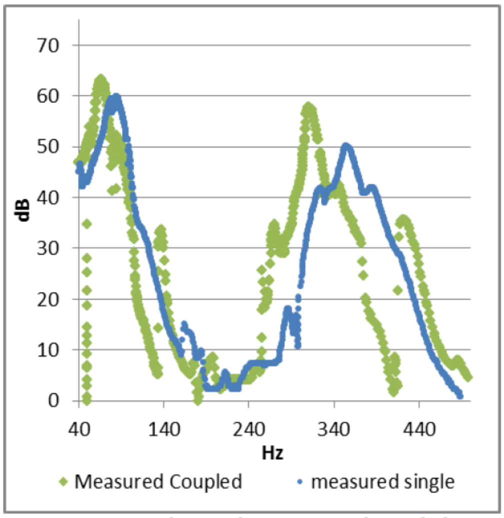

Figure 4. Green diamonds is measured coupled harvester I power output, the blue circles is measured single power output. The coupled power output is 1.7 times higher than the single power output.

Prototype II has a coupling of two screws with sleeves to hold the beam at the correct height, and a screw holder of FR4 with two holes for the screws that hold it together around the top cantilever were tested. The coupling weighed 1.8 g. A weight of 0.5 g is added to the top cantilever to make the two resonance frequencies closer for a broader bandwidth harvester. With this coupling the power output to the coupled harvester was 2.3 times higher compared with two single cantilevers (Figure 5). In figure 5 a simulation of the new coupling and the added weight is added and a comparison with two single cantilevers, one v21b and one v22b.

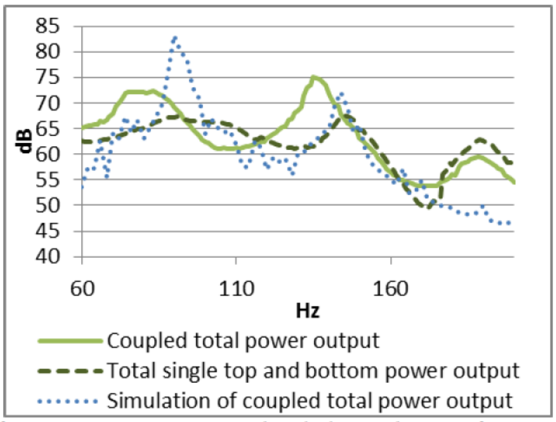

Figure 5. Measured results from Prototype II compared with the total output from two single cantilevers and compared with simulation of the improved coupling. The power output for the prototype II is 2.3 times higher than for two single cantilevers.

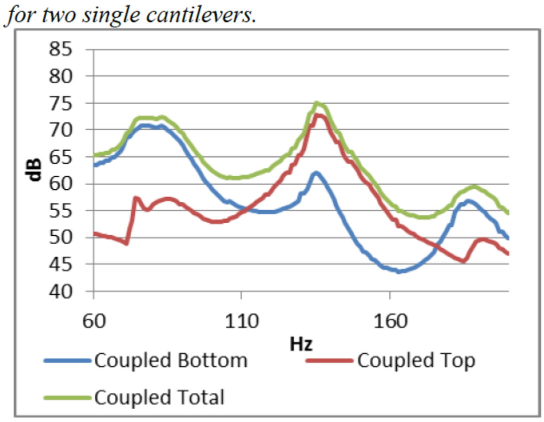

Figure 6. Coupled Prototype II where the green line is output power in total and the blue is the bottom cantilever and the red is the top cantilever.

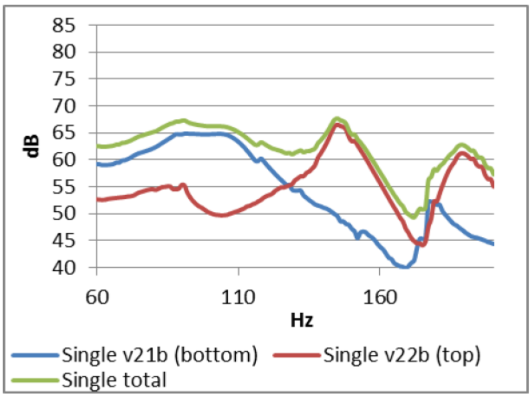

Figure 7. The two single cantilevers with the v21b as blue and v22b as red and the green line is the power output in total from both.

In Figure 6 the power output for the bottom and top cantilever contribution can be seen that adds to the total power output. In Figure7 the two measured single cantilevers are shown and put together to a total output from the two cantilevers. For the coupled harvester in Figure 6 the coupling effect on the bottom cantilever from the top cantilever is seen on the middle power peak, which is absent for the single v21b cantilever seen in Figure 7. In Figure 8 the coupled bottom cantilever power output is compared with the single v21b cantilever with a weight of 3.79 g as the attachment and the v22b weight in total. The primary and secondary resonance frequency for the single cantilever has a lower power output compared with the coupled cantilever which has three peaks where the left is primary, the rightmost one is secondary and the one in the middle is due to the magnification of the top cantilever. In Figure 9 the top coupled power output is compared with the single v22b power output. The coupled top has a higher power output at the primary resonance frequency but a lower output at the secondary resonance frequency.

5. Conclusion

By combining two piezoelectric cantilevers with a coupling, the measured power output is increased by 1.7 times compared to using the same cantilevers uncoupled; also the bandwidth is increased. With a lighter coupling of only 1.8 g and an added weight on the top cantilever the power output for the coupled harvester is increased to 2.3 times higher than for the two single cantilevers, and the power output peaks are brought much closer indicating that a broader bandwidth is reachable if the peaks are managed to merge together.

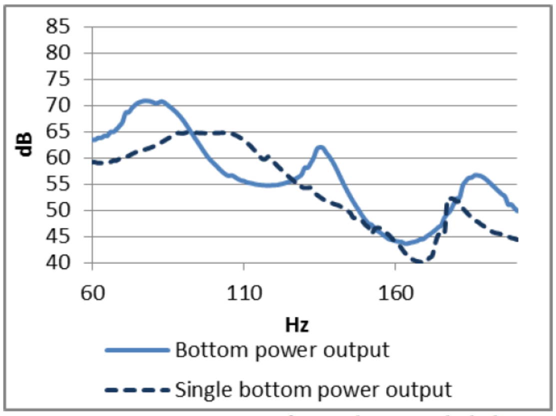

Figure 8. Power output from the coupled bottom cantilever compared with the same single cantilever. The middle peak on the coupled bottom line is the contribution from the coupling - working as an attachment and enhancing the strain on the bottom cantilever.

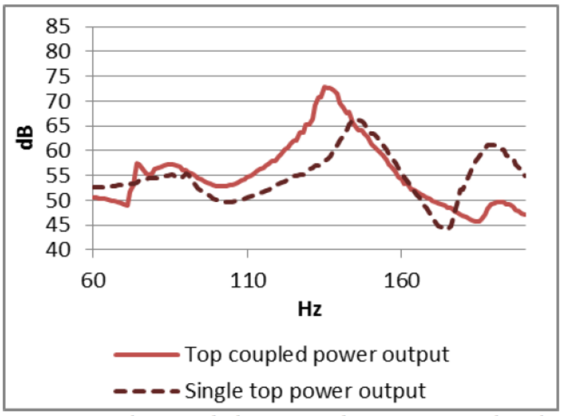

Figure 9. The coupled top cantilever compared with a single v22b. The coupled top cantilever is magnified by the bottom cantilever hence has a higher power output.

Acknowledgement

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