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Rectified Output Power Analysis of Piezoelectric Energy Harvester Arrays under Noisy Excitation

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Abstract.
    In the past decade, vibration energy harvesting has emerged as a potential alternative solution to power wireless sensor nodes. In real-world implementations, external excitation can be very noisy and includes noise signals in a wide frequency band. In order to accommodate operation under noisy excitation, arrays of energy harvesters with different resonance frequencies are often employed to improve responsibility. Due to the nature of noisy excitation and the difference in resonance frequencies, the response voltage signals from each harvester can be very different in amplitude, frequency and phase. In this paper, an array with two cantilevered energy harvesters is studied to analyze the rectified output power with different configurations using full-bridge rectifiers (FBR). The experiments show that connecting the two harvesters in parallel or in series before connecting with a FBR results in significant voltage cancellation due to phase mismatch. The most efficient way to extract energy is to use two FBRs for the two cantilevered energy harvesters, individually, and charge to one single storage capacitor connected at the outputs of the two FBRs.

1. Introduction
Among different vibration energy harvesting topologies, piezoelectric materials are widely adopted due to their high power density in mm^2 scale miniaturized energy harvesting systems [1]. Although many different active rectification circuits were proposed in the past decade [2–10], full-bridge rectifiers (FBR) are widely employed in commercially available systems due to their simplicity and stability. In alignment with miniaturization trends for wireless sensor systems, MEMS piezoelectric harvesters (PH) are drawing much research interest due to their compatibility with conventional CMOS technology [11–14].

A miniaturized piezoelectric harvester (PH) in 10's mm^2 scale can typically generate raw AC power up to 100's μW varying by different piezoelectric materials, structures and ambient conditions. In order to achieve the maximum possible output power, the PH is excited at its resonance frequency with a sinusoidal excitation signal under the highest operational excitation level. Although the resulting 100's μW peak power is promising to fully sustain operations of most wireless sensors, the usable rectified DC power in real-world implementations can be much lower than this peak value of around 10's μW. This significant power decrease is mainly due to two reasons: the wide frequency bandwidth of the real-world vibration conditions where the PH is implemented and the power extraction efficiency of the rectifier. In order to increase the effective frequency bandwidth for real-world noisy vibration environments, an array of two or more cantilevers with different resonance frequencies aiming at different frequency bands was designed in [15–18]. Due to the wide bandwidth of the excitation signal and the difference in resonance frequencies, the voltage signals generated in each cantilever can be very different in frequency, amplitude and phase. As a result, by simply connecting the harvesters up in series
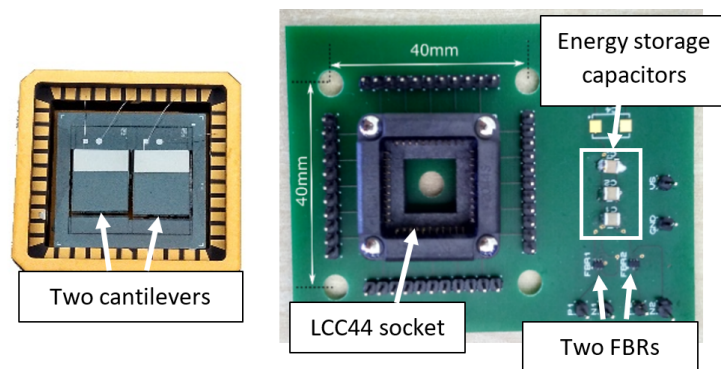
Figure 1: Photos of the MEMS device with an array of two micro-cantilevers (left) and the test board with one LCC44 socket and two FBRs (right).
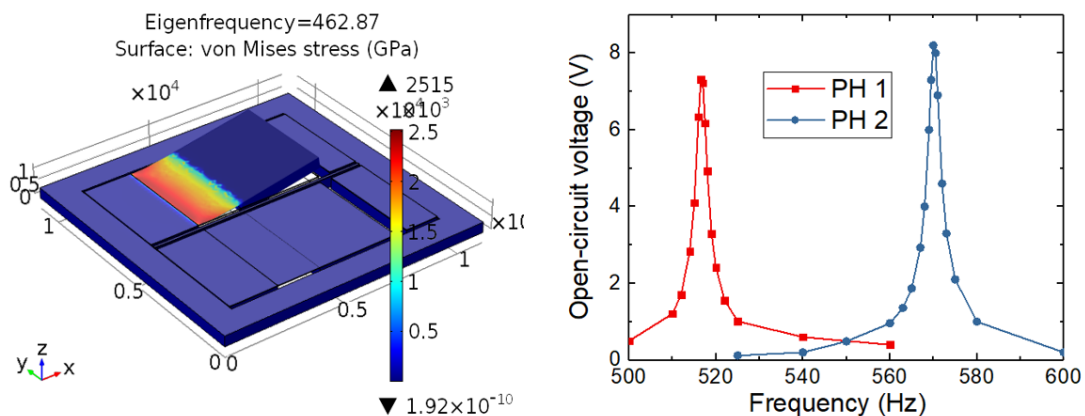

Figure 2: COMSOL model of the MEMS device with an array of two micro-cantilevers (left) and the measured resonance responses of the two cantilevers (right).

or parallel, it is possible to reduce the overall output power generated. Hence, power extraction methods from these cantilevers should be analyzed to increase the rectified DC power. In this paper, the rectified DC power of an array of two cantilevered piezoelectric harvesters (PH) using up to two FBRs under wide frequency-bandwidth excitation is analyzed and experimentally evaluated. The results show that each cantilever requires an individual FBR to extract and rectify the energy. By contrast, if only one FBR is employed while the two micro-cantilevers are connected in parallel or series before connecting with the FBR, the resulting DC power is extremely low due to the voltage cancellation cased by out-of-phase voltage combination.

2. Experiments

Figure 1 shows the fabricated MEMS device with an array of two cantilevers and the test board with two FBRs and a few energy storage capacitors. The size of the MEMS die is 11 mm × 11 mm and the two micro-cantilevers can be seen in the figure. During the measurements, the MEMS device is placed in a LCC44 leadless chip carrier, which is placed in the LCC44 socket on the test board fixed on a shaker.

Figure 2 shows the COMSOL model for the MEMS device comprising an array of two cantilevers. The device is designed in a MEMS process with AlN (Aluminum Nitride) as the piezoelectric material and the simulated model is with the same dimension as the device to be tested in the following experiments. The resonance frequencies of the two cantilevers are designed to be 463 Hz and 501 Hz, respectively. Due to fabrication tolerances, the fabricated MEMS cantilevers are measured to have resonance frequencies at 517 Hz and 570 Hz, respectively, as shown in the right sub-figure of Fig. 2
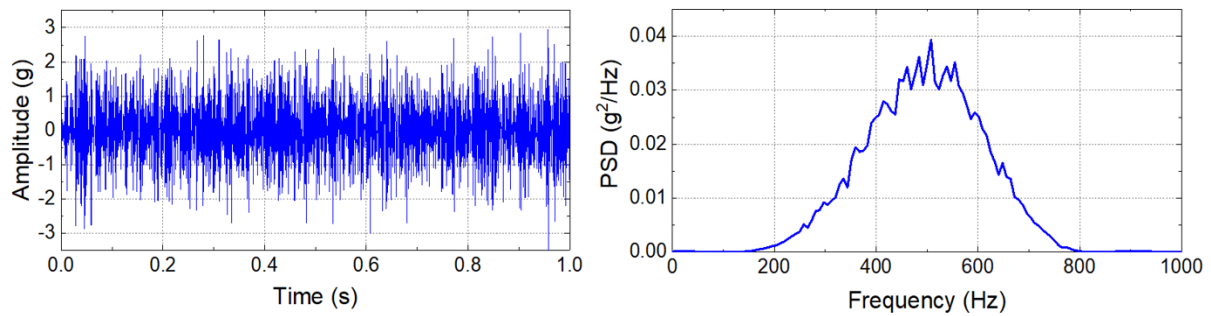
Figure 3: Noisy excitation profile signal centered at 500 Hz in time-domain (left) and frequency-domain (right).
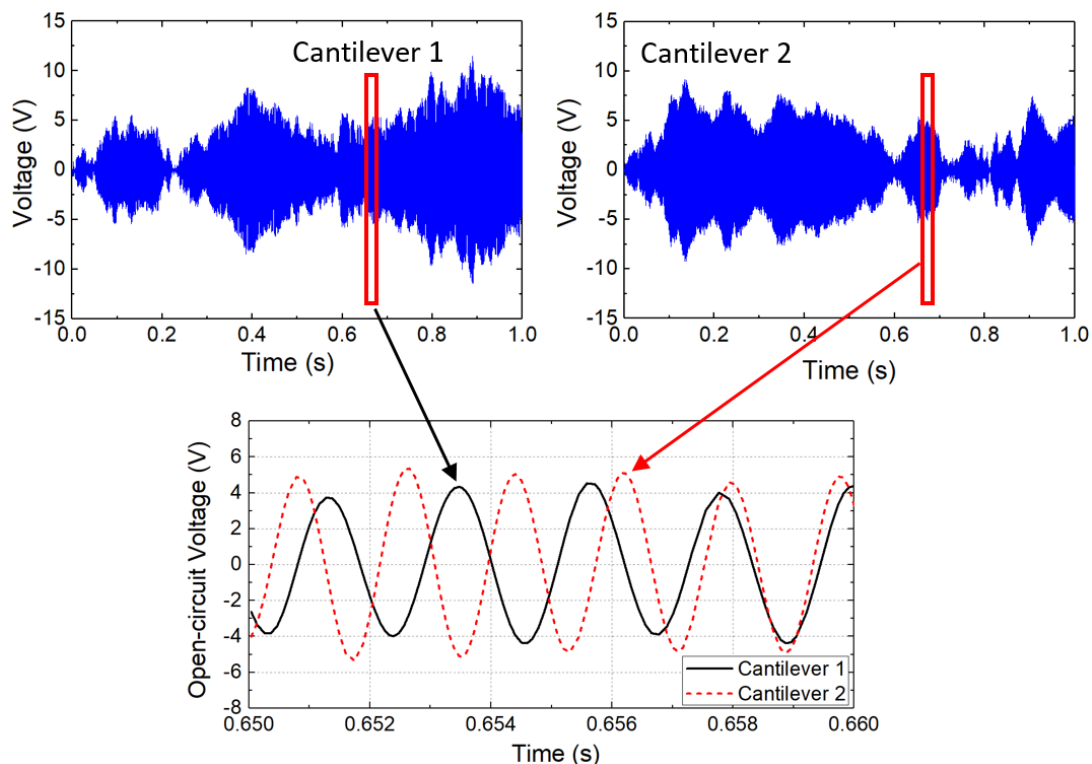

Figure 4: Simulated open-circuit voltage signals from the two micro-cantilevers under noisy excitation.

A vibration profile is used for following experiments instead of using a sine wave signal to mimic the real-world excitation. The time-domain and frequency-domain plots of the profile is shown in Fig. 3. This vibration profile has a peak frequency at 500 Hz with broadband noise. The MEMS device with two cantilevers is excited under this profile.

Fig. 4 shows the simulated open-circuit voltage from the two cantilevers excited with the profile data shown in Fig. 3. It can be seen that the output signals from the two cantilevers are significantly different in amplitude in the two upper sub-plots of Fig. 4. A zoomed-in figure shows the two signals in a 10-ms period and it shows that there is a significant phase mismatch for the two cantilevers due to the difference in the response characteristics. If the two cantilevers are connected in parallel or in series before connecting to a FBR, voltage cancellation due to phase mismatch can result in significant energy waste.

The following measurements are split into two parts: testing the two cantilevers separately and testing them together in different connection configurations. The left sub-figure in Fig. 5 shows the measured DC power while the two cantilevers are tested individually. In the plot,
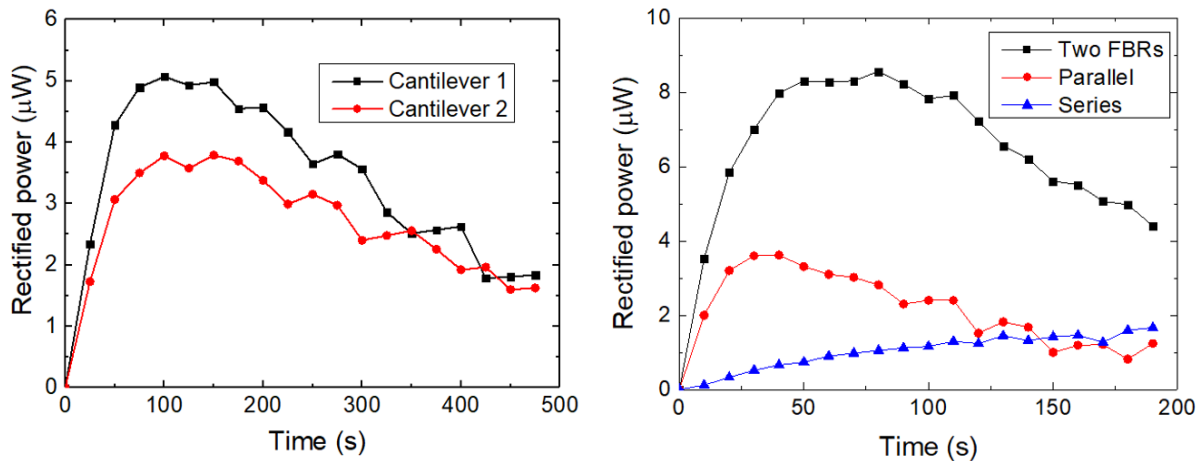
Figure 5: Measured rectified DC power. Left: DC power by two cantilevers while measured individually. Right: Two cantilevers are measured together using two FBRs for each one and while connecting them in parallel and series before connecting to a single FBR.

Table 1: Summary of measurement results

Individual tests		Two cantilevers together	
Cantilever	DC power	Type	DC power
No. 1	$5\,\mu$W	Using two FBRs	$8.4\,\mu$W
No. 2	$3.8\,\mu$W	One FBR (parallel)	$3.3\,\mu$W
Mathematical sum	$8.8\,\mu$W	One FBR (series)	$2.7\,\mu$W

the horizontal axis shows a representative measurement time axis plotted up to 500 s and the vertical axis shows the rectified DC power. The measurements were performed to charge energy storage capacitors via a FBR and the DC power is then calculated from the measured voltage across capacitors for every 25 seconds. These two measurements show that the two cantilevers can output peak power values of $5.0\,\mu$W and $3.8\,\mu$W, respectively, when they are measured individually.

The two cantilevers are then measured together to show the DC power under different configurations. The results are shown in the right sub-figure of Fig. 5. For the first configuration (labeled as "Two FBRs"), two FBRs are used (one for each cantilever) and the outputs of the two FBRs are connected together to charge sharing energy storage capacitors. In this case, measured peak DC power is around $8.4\,\mu$W. For the following two configurations, only one FBR is employed and the two cantilevers are connected in parallel/series prior to connecting to the FBR. In these two cases, the measured DC power levels are around $3.3\,\mu$W and $2.7\,\mu$W, respectively.

The measurement results are summarized in the table 1. It can be seen that, due to the phase mismatch between the two cantilevers under noisy excitation, the DC power values for parallel and series configurations are much lower than the mathematical sum of the power values individually measured from the two cantilevers. This is due to the voltage cancellation when excited under noisy excitation. When each cantilever is connected up to a separate FBR, the measured output power is almost the mathematical sum and there is very little energy loss in this case.

3. Conclusion
This paper analyzes the phase mismatch for multiple piezoelectric cantilevers connected up in either parallel or series excited under noisy excitation. A MEMS piezoelectric harvester with

an array of two micro-cantilevers were fabricated to test the theory. During the measurements, a vibration profile with broadband noise is used to excite the MEMS device. Simulation and experimental results show a significant voltage cancellation if the micro-cantilevers are directly connected in parallel or in series prior to rectification. In order to extract and rectify energy generated from an array of cantilevers, each cantilever requires an individual FBR in order to eliminate voltage cancellation and to maximize the extracted DC power. If only one FBR is employed by connecting all the micro-cantilevers in parallel or in series, the resulting DC power can be extremely low due to the phase mismatch across the cantilevers.

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