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Nonlinear Multi-Frequency Converter Array for Vibration Energy Harvesting in Autonomous Sensors

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Abstract

This work proposes and experimentally validates a vibration energy harvester which combines the multi-frequency and nonlinear approaches into a converter array. The converter array consists of four piezoelectric cantilevers composed of ferromagnetic substrates with screen-printed lead zirconate titanate (PZT) layers coupled with a single permanent magnet elastically suspended on the array base in order to create a nonlinear behaviour. The presence of a moving magnet and the possibility to realize cantilevers with different potential curves can be useful to obtain a collective nonlinear behaviour due to strong coupling irrespective of the amplitude of the mechanical excitation, therefore increasing the overall effectiveness of the converter array. The experimental results confirm that combining cantilevers with different potential curves can be useful to obtain a collective bistable behaviour, therefore increasing the overall effectiveness of the converter array.

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Keywords: piezoelectric; nonlinear multi-frequency converter; energy harvesting; broadband vibrations.

1. Introduction

Piezoelectric energy harvesters form vibrations and motion can be based on linear resonant converter systems which achieve the best harvesting effectiveness when operated at mechanical resonance, but they are sub-optimal with frequency-varying and wideband vibrations [1]. The resonance condition is however hard to maintain when the excitation is not controllable or intrinsically frequency-variant over a broad range. The converter damping can be increased to widen the response bandwidth but this decreases the peak output level. Therefore, a trade-off in general results between the bandwidth span and the achievable

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output level and thus the performances of the converter strongly depend on the vibration frequency. The exploitation of multi-element harvesters combining the outputs from multiple converters with different frequency responses into a Multi-Frequency Converter Array (MFCA) was investigated [2]. However, for a given excitation frequency, mostly one single converter at a time contributes to the output power, with a corresponding limitation in the whole power density. Furthermore, for millimeter-scale converters, the resonant frequency is generally higher than typical values of environmental mechanical vibrations. To widen and translate toward lower frequencies the bandwidth of the converter the exploitation of nonlinear effects [3] and in particular of bistable systems was introduced creating external nonlinear forces by means of magnets or using buckled beams [4-7]. The presence of bistability makes the system capable to rapidly switch between the stable states, thereby increasing the converted power and widening the bandwidth of the harvester. With respect to linear converters, bistable converters are less dependent on the frequency of the input vibrations and they can be made responsive to broadband or random vibrations. On the other hand, due to nonlinearity the response becomes a function of the vibration magnitude [8-9]. To overcome these limitations, the combination of the multi-frequency and nonlinear approaches into an innovative converter array is proposed in order to increase and shift the converter equivalent bandwidth towards lower frequencies without worsening the peak response.

2. Nonlinear Multi-Frequency Converter Array

The nonlinear multi-frequency converter array is composed of four piezoelectric cantilevers made by a ferromagnetic steel substrates with PZT layers coupled with a permanent magnet elastically suspended on the array base, as shown in Fig. 1.

The piezoelectric converters are realized by screen-printing low-curing-temperature PZT films on stainless steel cantilevers. The PZT ink is composed of commercial powders (Piezokeramica-APC 856) and a low-curing-temperature polymeric binder. The film was cured at 150 °C for 10 min and then poled at 300 V at the same temperature for the same time. The substrates have planar dimensions of 40 mm x 5 mm and thickness between 100 μm and 200 μm , while the PZT layer thickness is about 65 μm . Differences in steel thickness and tip masses among cantilevers determine different resonant frequencies. By adjusting the distance and vertical alignment from the magnet, each cantilever presents a different potential energy function and frequency response. The moving magnet allows to trigger the nonlinearity and bistability by mutual interactions among converters which therefore become strongly coupled.

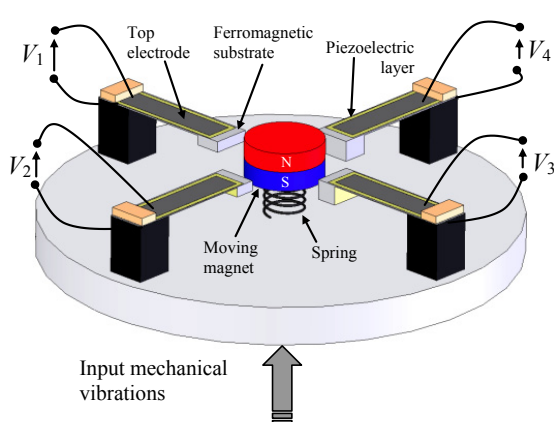


Fig. 1. Schematic diagram of the nonlinear multi-frequency converter array.

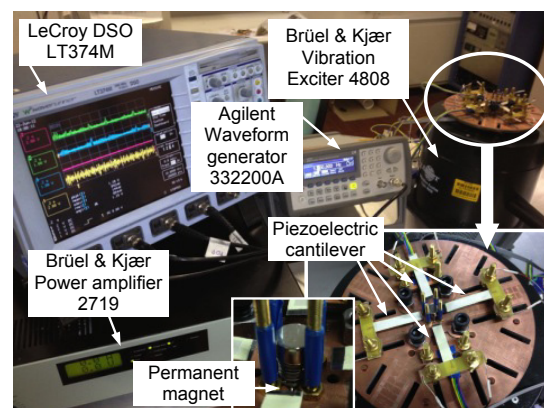


Fig. 2. Experimental setup for the dynamic characterization of the converter array.

3. Experimental Results

The nonlinear multi-frequency converter array has been characterized both in the linear regime, obtained without the magnet, and nonlinear regime with the experimental setup shown in Fig. 2. The typical electrical impedance of the piezoelectric cantilevers is a capacitance of 560 pF and a parallel resistance in the order of 100 MΩ measured with a HP4194A impedance analyzer at 100 Hz.

The measured resonant frequencies of the cantilevers for the linear configuration and linearized resonant frequencies around the upper and the lower equilibrium points for the nonlinear approach are reported in Table 1. Resonances are determined by measuring the frequency of the open circuit output voltages generated by converters as a result of suitable small impulsive mechanical excitations. Differences in the linearized resonant frequencies for the two equilibrium points are due to the imperfect vertical alignment of cantilevers with respect to the permanent magnet.

Preliminary results were obtained with a magnet held in a fixed position on the base horizontally aligned with all the cantilevers. The converter array was excited by a Brüel & Kjær 4808 vibration exciter with a band-pass filtered white-noise acceleration with different peak values up to 3 g in the linear and nonlinear conditions. Fig. 3 shows that at parity of mechanical excitation, the nonlinear approach typically provides an increase in the output voltage over the linear approach.

Fig. 4 shows the RMS open circuit output voltages delivered by two cantilevers with different mechanical characteristics as a function of the vibration peak amplitude, both in the linear and nonlinear approaches. The open circuit RMS output voltages of the four cantilevers are acquired by a LeCroy LT374M digital oscilloscope. In the nonlinear approach, the converters present different behaviours depending in which equilibrium state they operate. When the converters operate at small amplitudes in the lower wells, the outputs in the nonlinear case are lower than in the linear case due to the higher confinement. However, for vibration amplitudes larger than about 1.2 g, the cantilevers are able to bounce between the two equilibrium points, with a significant increase of the output power.

The possibility to realize different cantilevers with different potential curves can be useful to obtain a collective bistable behaviour with a reduced dependency on the sensitivity of each converter to the amplitude of the mechanical excitation, therefore increasing the overall effectiveness of the converter array.

4. Conclusion

A multi-frequency nonlinear piezoelectric energy converter array for energy harvesting from mechanical vibrations was presented. The combination of the nonlinear and multi-frequency approaches allows increasing and shifting the converter equivalent bandwidth towards lower frequencies without worsening the peak response. The possibility to realize different cantilevers with different potential curves can be useful to obtain a collective bistable behaviour with a reduced dependency on the sensitivity of each converter to the amplitude of the mechanical excitation, therefore increasing the overall effectiveness of the converter array.

Table 1. Characteristics and measured resonant frequency of cantilevers for the linear and the nonlinear conditions.

		Cantilever 1		Cantilever 2		Cantilever 3		Cantilever 4	
Steel thickness		200 μm		100 μm		200 μm		100 μm	
Tip mass		no		yes		no		yes	
Resonant frequency	Linear	150 Hz		27 Hz		154 Hz		31 Hz	
	Nonlinear	<i>Upper</i>	<i>Lower</i>	<i>Upper</i>	<i>Lower</i>	<i>Upper</i>	<i>Lower</i>	<i>Upper</i>	<i>Lower</i>
		137 Hz	157 Hz	45 Hz	46 Hz	145 Hz	174 Hz	49 Hz	71 Hz

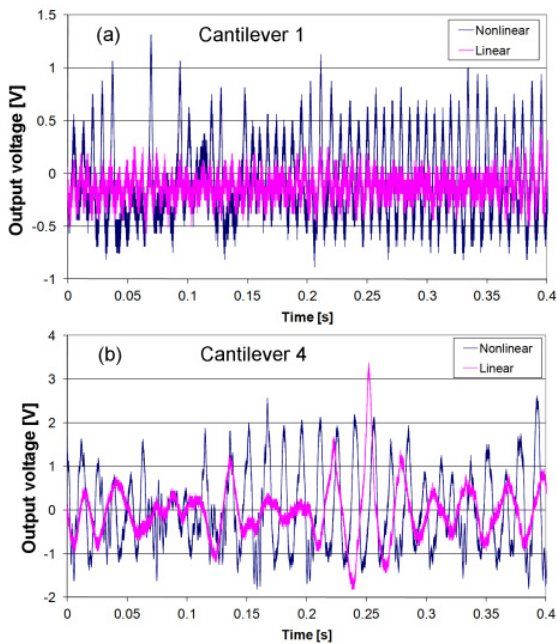


Fig. 3. Measured open-circuit output voltage of two different piezoelectric cantilevers for linear and nonlinear conditions.

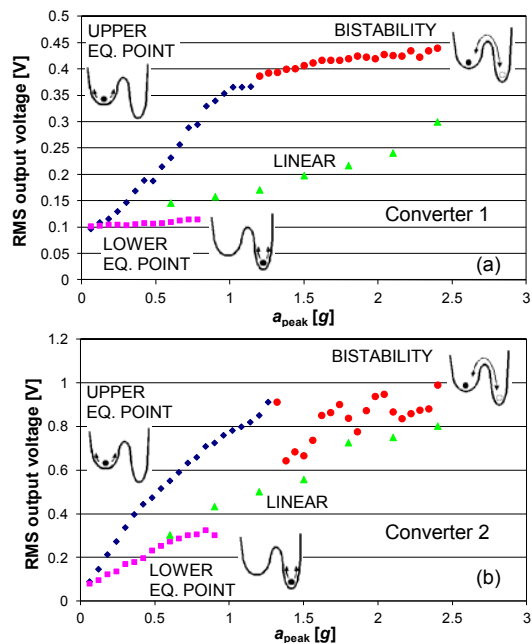


Fig. 4. Measured RMS output voltage of two different piezoelectric cantilevers for linear and nonlinear conditions.

Acknowledgements

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