BISTABLE MULTIPLE-MASS ELECROSTATIC GENERATOR FOR LOW-FREQUENCY VIBRATION ENERGY HARVESTING

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ABSTRACT

This paper reports a novel vibration energy harvester (VEH) design consisting of a double–mass contactless frequency–up converter with buckled clamped–clamped beams. The vibration to electricity conversion is performed through a MEMS silicon micro electrostatic vibration energy harvester (e-VEH) based on in–plane gap–closing interdigitated combs. Despite the fact that the converter itself is designed to resonate at 162 Hz, the use of the bistable stage as mechanical exciter allows a gain factor of hundred when converting low–frequency vibrations (20–40 Hz) into electrical energy.

INTRODUCTION

The harvesting of ambient energy in the shape of vibrations is considered an key technology to enable self-sustained, long-lasting and free–maintenance wireless electronics [1-3]. Kinetic energy is abundantly available in industrial plants, transportations, infrastructures and also human activities. However, mechanical vibrations from natural and artificial sources are pretty much weak and located below few hundreds of hertz. On the other hand, typical vibration energy harvesters (VEHs) are resonant spring–mass–damper systems that only work efficiently at resonance frequency. In order to enlarge the bandwidth of harvesting devices some alternative concepts have been proposed in recent years: self-tuning resonators [4], piezoelectric cantilevers arrays [5, 6] and mechanical frequency-up conversion systems [7, 8]. In addition, nonlinear Duffing–like piezoelectric oscillators have already been shown to be advantageous for harvesting energy under random noise and low–frequency vibrations [9-11]. The conversion of mechanical energy at low frequencies has been also approached via frequency–up conversion techniques [4]. However, piezoelectric and electromagnetic converters are still quite bulky, while electrostatic vibration harvesters are more suitable to be implemented into MEMS–scales [12, 13]. Nevertheless, at sub–centimeter dimensions the resonance quickly increases from few hundreds hertz to several kHz depending on the proof mass, thus deteriorating the capability to harvest energy at frequencies below 100 Hz. Recently, a multiple degrees of freedom (multi–DOF) electrostatic system using frequency-up conversion have been proposed [14] to capture low frequency vibrations. However, this device uses contacting parts that increase the mechanical damping and it is capable of generating few nano-watts.

The novel approach reported in this paper combines the advantages of bistability with a contactless double mass frequency–up conversion system by employing a bistable exciter with a silicon micro–electrostatic VEH. The use of buckled beams for implementing the bistability makes the system free from magnetic elements.

DESCRIPTION OF THE SYSTEM

Figure 1 represents a scheme of the harvester model, while, a prototype photograph is shown in Figure 2(a). In this prototype the exciter consists on an aluminum mass of size of 50 × 40 × 15 mm^3 suspended on the middle point by two steel beams of 46 mm of free length × 6 mm of width × 0.1 mm of thickness that are clamped to the rigid frame by their both ends. The beams can be buckled by means of a micrometric screw. In this condition, the resulting bistable system acts as exciter for the resonant generator on which it is anchored. The kinetic-to-electrical energy conversion is executed by a silicon MEMS electrostatic vibration energy harvester (e-VEH) based on in–plane gap–closing interdigitated combs. This device is fabricated by DRIE through a 380-µm-thick silicon wafer which in turn is bonded on a glass wafer. The overall die surface measures about 10 × 10 mm^2. The fingers have a length of 2 mm, width of 30 µm and are separated by a gap of 45 µm.

When the system is shaken at low frequencies the exciter mass jumps between the two stable positions of its Duffing–like potential energy. Each jump imparts a wideband mechanical impulse to the proof mass of the micro e-VEH which is thus excited at its resonance frequency, f_r = 162 Hz. Therefore, the mechanical frequency-up conversion occurs when the frequency of the input vibration corresponds to the inter-well resonance, f_{iw} that can be within 20–40 Hz depending on the buckling height of the beams, h_b = 0.8–1.5 mm. Although the tested prototype includes an exciter mass of centimeter size, the main objective here is to validate the proposed operating principle that in the future can be fully integrated within the silicon MEMS.

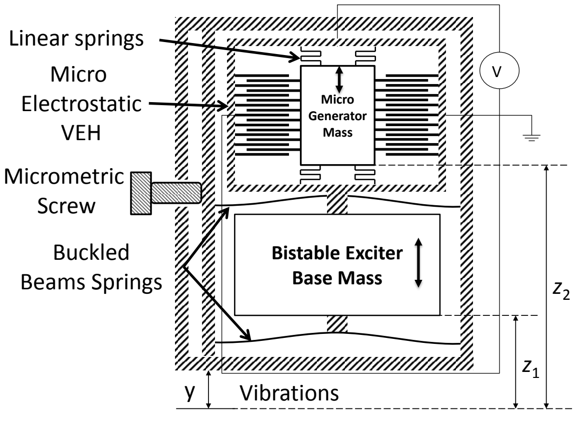

Figure 1: Scheme of the bistable multiple-mass VEH. The size of the micro electrostatic VEH is enhanced to facilitate the view but the illustrated configuration be applied at different scales.

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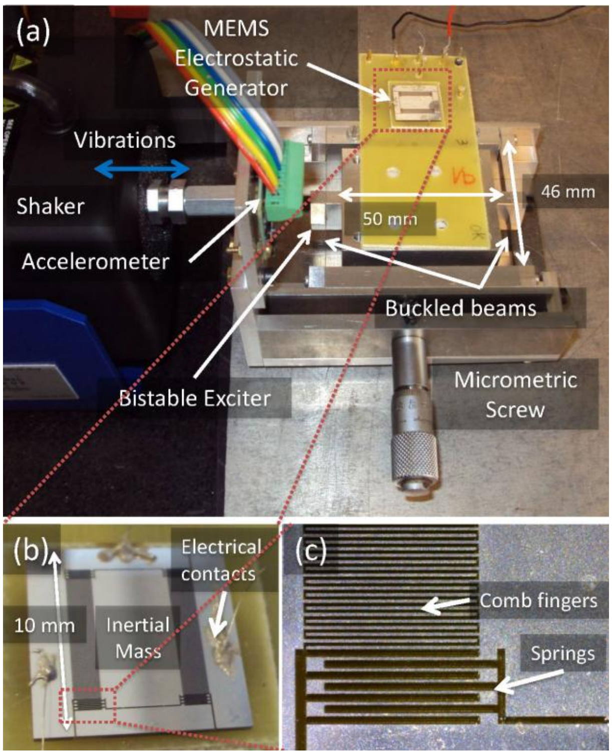

Figure 2: (a) Picture of harvesting device prototype. (b) Expanded view of silicon comb micro electrostatic VEH with (c) magnification of comb fingers and silicon springs.

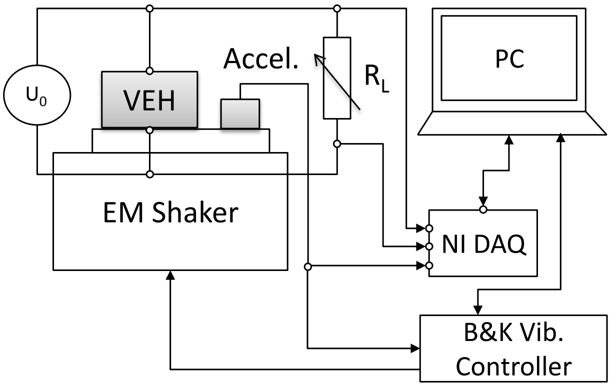

Figure 3: Scheme of the experimental equipment.

EXPERIMENTAL SETUP

The used experimental setup is outlined in Figure 3. The harvesting device prototype is mounted onto an electromagnetic shaker that provided the vibrations (TMS, model K2007E01 with integrated power amplifier). The vibration input is generated and handled by a vibration controller (Brüel & Kjær) through the feedback of an accelerometer (Freescale Semiconductor, model MMA7361L, with 800mV/g of sensitivity). The micro electrostatic VEH is precharged a voltage U_0 and the output current is fed through a variable resistance R_L variable resistance (1 kΩ–0.5 MΩ) connected in series. All the signals are then recorded through a data acquisition card (National Instruments, model USB-6211) handled with a PC with a LabView program.

Table 1: Model parameters for the VEH prototype.

Parameters	**Value**
MEMS micro e-VEH	
Proof mass, m_0	66 mg
Elastic stiffness, k_0	68 N m^{-1}
Mechanical resonance, f_r	162 Hz
Active area, A_0	10 × 10 mm^2
Gap between fingers, g_0	45 µm
Optimal load resistance, R_{opt}	5.3 MΩ
Device thickness, t_d	0.38 mm
Fingers length, l_f	2 mm
Fingers width, wf	30 µm
Bistable exciter	
Exciter mass, m_e	0.246 Kg
Main resonance, f_e	20–40 Hz
Beam free length, l_b	46 mm
Beam width, w_b	6 mm
Beam thickness, t_b	0.1 mm
Buckling height, h_b	0.8–1.5 mm

A first characterization of the MEMS micro e-VEH was carried out for identifying the model parameters that are listed in Table 1. Subsequently, two testing sessions were performed under sine sweeping and band–limited colored random noise for $a_i = 0.1 - 0.2g$ rms ($g = 9.81$ m/s^2) of base acceleration and precharge voltage $U_0 = 2.5$. All the measures were carried out comparing the system behaviour both with and without the bistable exciter.

RESULTS AND DISCUSSION

Frequency sweeping

Figure 3(a) and (b) display the RMS voltage and the corresponding power respectively, normalized by the acceleration base, for harmonic input under frequency sweeping. These values are measured across the identified optimal load resistance (5.3 MΩ). In particular, at each frequency of the sinusoidal input, we compare the performance of the harvester with buckled–beam base exciter (bistable mode) versus the normal operation of the standing alone electrostatic generator (normal mode) mounted on the shaker without the bistable exciter. The sweep-up and sweep-down do not perfectly overlap due to the nonlinear behavior of the structure.

It is important to note that the harvested power increases of more than 100 times at low frequencies, in the interval between 20 and 50 Hz, for the bistable mode compared to normal mode of the standing alone micro e-VEH. On the other hand, the normal operation results more efficient at higher frequencies, within 140 and 180 Hz. This is due to the mechanical filtering effect of the oscillating bistable mass that dim the vibration of the MEMS proof mass in this range.

Nevertheless, the response of the harvester in bistable mode is still surprisingly good between 110 and 170 Hz. In fact, a shift of about 20 Hz of the power spectrum interval toward lower frequencies is observed. This is another beneficial effect for the VEH to match the requirements of real world vibrations [2].

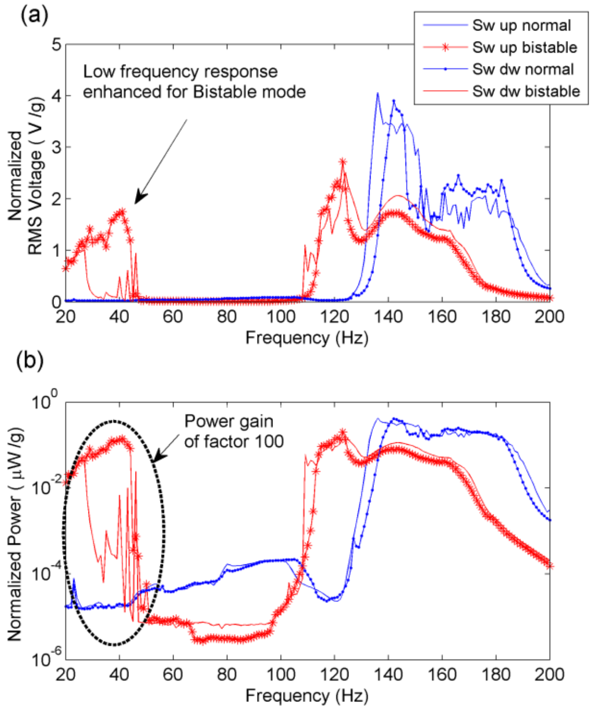

Figure 3. (a) RMS Voltage and (b) power response normalized acceleration amplitude (0.02 g) under sinusoidal frequency sweeping. The comparison regards the structure with buckled (bistable) beams versus the normal operation of standing alone electrostatic generator (normal) without the bistable exciter.

Random noise

Figure 4(a) and (b) show the normalized RMS voltage and power spectrum when the system is excited under colored noise respectively. In particular, low-frequency exponentially correlated noise with autocorrelation time of 0.01s is used. So that, the corresponding band is limited by a cut-off frequency of 16 Hz. Here, we investigate the system in three configurations: with the bistable exciter with buckled (bistable mode) and unbuckled (monostable mode) beams; and then versus the standing alone generator (normal) as previously. In this way, we are able to analyze the effect of mechanical filtering due to the insertion of the bistable exciter when its beams are both buckled (with buckling height, $h_b = 1$ mm) or unbuckled ($h_b = 0$ mm).

It must be noted that in bistable regime, even under very low−frequency random vibrations (below 16 Hz which is the noise cutoff frequency), the generator resonates in the range 75−200 Hz (mechanical frequency is half the frequency of the output voltage). The bandwidth response and power of the VEH is 5 times amplified within 100 and 200 Hz in bistable mode versus normal operation.

Figure 5(a) and (b) illustrate the output voltage relative to the buckled and unbuckled beam configuration respectively. It is evident the amplitude spikes produced by the inter-well jumps that impart wideband pulses. In between the spikes the exciter mass vibrates within one of its stable position so transferring only a part of its kinetic energy to the micro e-VEH. Even in this case the voltage still maintains a good level compared to normal mode.

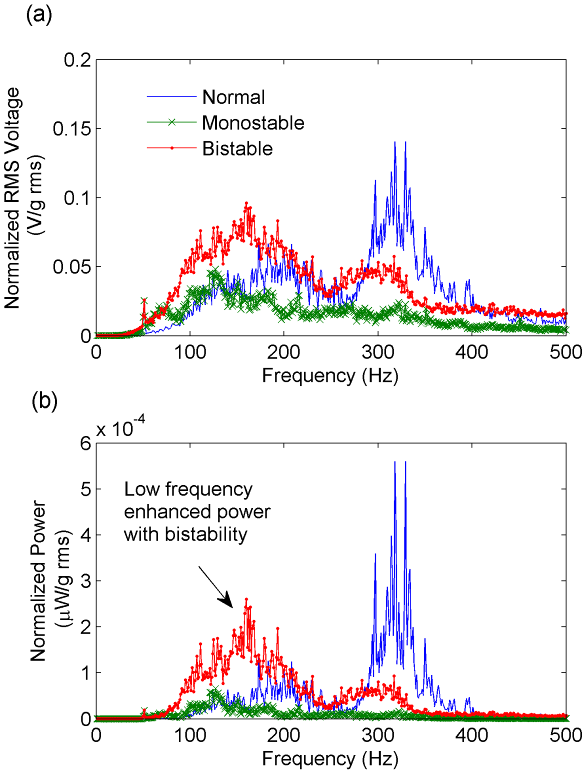

Figure 4: (a) RMS Voltage and (b) power spectrum normalized by the acceleration amplitude (0.15 g rms) under colored noise (15 Hz of cutoff frequency). The comparison regards the structure with buckled (bistable) and unbuckled (monostable) beams versus the operation of standing alone electrostatic generator (normal) without the bistable exciter.

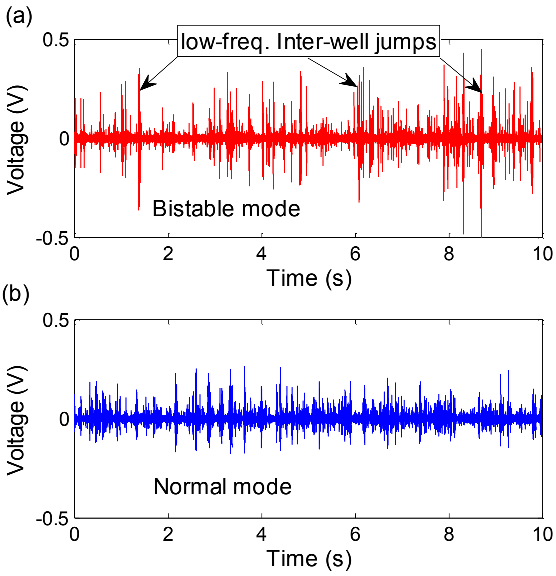

Figure 5: Output voltage under colored noise with autocorrelation time of 0.01 s (cut-off frequency of 16 Hz) corresponding to the VEH in (a) bistable configuration mode (buckling height of 1 mm) and (b) normal mode respectively for acceleration amplitude of 0.15 g rms. Note the voltage spike in bistable mode due to the inter-well jumps with consequent impulse-like excitation.

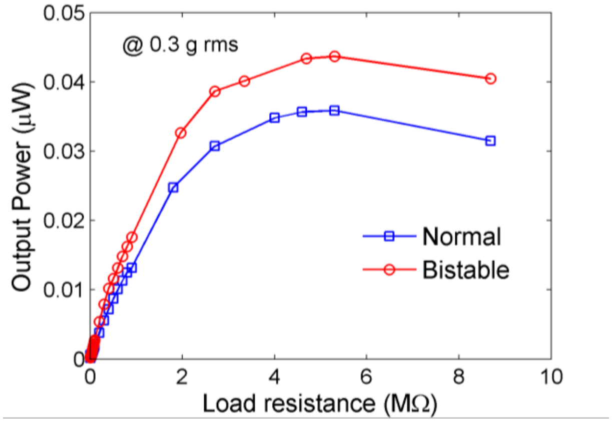

Figure 6: Output power versus load resistance under colored noise at 0.3 rms of base acceleration.

Figure 6 shows the harvested power under colored noise at 0.3 g rms of base acceleration. It can be observed that even in the bistable mode (with bucking around 0.5 mm) the system presents the same optimal load of normal operation, corresponding to 5.3 MΩ. This result confirms a global better performance of around 20 % for the bistable mode under low frequency noise. It is also important to underline that the overall efficiency of the bistable mode depends on the buckling height h_b that affects the potential barrier. An optimal value must be found in relation to the base acceleration.

CONCLUSIONS

This paper introduced a double–mass vibration energy harvester embedding a bistable buckled–beam system for frequency–up conversion. This concept aims at increasing the energy harvesting efficiency for low–frequency vibrations. The kinetic–to–electrical energy conversion was performed through a silicon MEMS micro electrostatic generator based on interdigitated combs. A device prototype was fabricated and experimentally investigated under harmonic frequency sweeping at 0.2 *g* rms and band-limited colored noise 0.15 *g* rms with a precharge voltage of 2.5 V.

When in buckled-beam bistable configuration, the electrostatic generator shown a gain factor of 100x in harvesting low−frequency vibrations (20−40 Hz) versus the normal operation mode, despite of the fact that the converter itself was designed to resonate at 162 Hz. In addition, the power response is shifted towards lower frequencies, both under frequency sweeps and colored noise. This effect represents an additional benefit for VEHs by considering that real vibration sources are usually located below few hundreds of hertz.

Moreover, the presented concept can be also applied to different transduction techniques.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of FP7 Marie Curie Intra–European Fellowship (IEF) funding scheme (NEHSTech, Grant No. 275437) at Université de Paris-Est, ESIEE Paris.

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