

ELECTROSTATIC GENERATOR WITH FREE MICRO-BALL AND ELASTIC STOPPERS FOR LOW-FREQUENCY VIBRATION HARVESTING

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ABSTRACT

We present a new MEMS electrostatic vibration harvester that exploits mechanical frequency amplification by multiple-mass impacts in combination with elastic stoppers. When the system is shaken at low frequency (10-60 Hz) a tungsten micro-ball impacts within the oscillating proof mass of the harvester transferring kinetic energy to the gap-closing comb transducer which in turns resonates at its natural frequency (92 Hz). In addition, elastic stoppers amplify the proof mass and ball velocity throughout collision with the fixed frame. Output power between 0.25 and 0.45 μW is achieved at 0.3-g amplitude and only 15 V bias in the range of 10-60 Hz with a -3db bandwidth of 50 Hz.

INTRODUCTION

Future wireless electronics must be independent from powering sources and have the capability to operate for very long time without maintenance in order to enable smart applications [1]. The possibility for wireless sensors to find power supply where they are deployed open vast sceneries of intelligent applications for healthcare, transportation, surveillance, military and industrial monitoring. In this regard, kinetic energy in the shape of vibrations is abundantly available in the real world such as industrial plants, transportations, infrastructures and biological beings. However, mechanical vibrations from natural and artificial sources are inconsistent and mostly located in between 2 and 100 Hz. Typical commercial vibration energy harvesters (VEHs) are based on linear mechanical oscillators that efficiently work within few hertz around the resonant frequency. Regardless of the type of conversion method, at MEMS dimensions, the harvester resonance quickly increases up to several kHz depending on the weight of the inertial mass and on the equivalent stiffness of the suspension springs. Therefore, the mismatch between real world vibrations frequency (2-100 Hz) make MEMS linear harvesters unpractical. New approaches have been recently investigated to widen the operating bandwidth, such as nonlinear piezoelectric oscillators [2], self-tuning resonators [3] and piezoelectric cantilevers arrays [4], although with centimeter-sized demonstrators. In order to address the problem of extracting energy from low-frequency vibrations, frequency-up conversion system have also been proposed by means of piezoelectric or electromagnetic generators [5]. However, these prototypes were quite bulky, whereas, electrostatic vibration energy harvesters (e-VEH) are more suitable for MEMS fabrication [6]. Recently, a multiple-mass electrostatic harvester exploiting frequency-up conversion

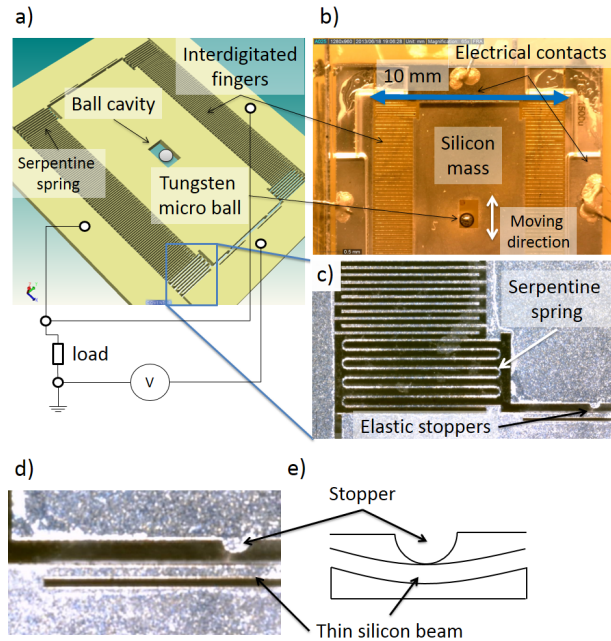


Figure 1: (a) Computer drawing of the gap-closing MEMS electrostatic VEH with electrical connection scheme of bias/output voltage. (b) Microscope photograph of the device (65x of magnification) with (c) magnified view (90x) of mechanical serpentine springs, (d) elastic stoppers with thin silicon beam and (e) sketch of stopper with beam.

have been proposed by Fu et al [7] to capture low frequency kinetic energy. However, this device shown few nano-watts of generated power.

The use of multiple impacting masses was shown to be advantageous for electromagnetic vibration harvesters [8, 9]. With reference to electrostatic generators, Lee and Halvorsen recently proposed a device exploiting internal mass impacts with end stops to widen the frequency response [10]. Galchev et al. [11] shown an original springless inertial harvester for converting low-frequency motion into electricity by means of magnetic ball. The authors of this work also presented a wideband spring-mass gap-closing MEMS e-VEH with nonlinear mechanical and electrical features.

The concept reported here improves the previous device by exploiting a mechanical frequency amplification through multiple-mass impacts of a heavy tungsten micro-ball in combination with elastic stopper bouncing effect. The design, fabrication and testing of a new prototype of silicon gap-closing MEMS electrostatic VEH assembled with a

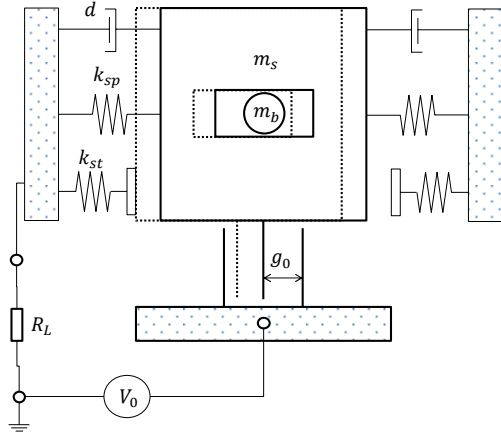


Figure 2: Model of the MEMS e-VEH.

tungsten micro-ball is here presented. The system takes advantage of the free movement of the micro-ball housed inside a rectangular cavity of the silicon proof mass that can capture low-frequency vibrations and transfer kinetic energy to the electrostatic transducer.

SYSTEM DESIGN AND PRINCIPLE

Figure 1(a) presents the 3D drawing of the MEMS-eVEH, while figure 1(b) and shows a microscope photograph of the generator with magnified (90x) particular of the serpentine support springs and elastic stoppers. Figure 1(d) shows an expanded view of elastic stoppers with a thin silicon beam of the fixed part and (e) schematics of the stopper when impacting on the silicon beam. The system model is illustrated in figure 2. The electrostatic transducer consists of a bulk silicon in-plane gap-closing interdigitated-combs with the proof mass suspended by serpentine springs of 20 μm of thickness. The comb capacitor is pre-charged by an initial bias voltage V_0 that span from 10 to 20 V. A tungsten carbide micro-ball of 0.8 mm of diameter is housed inside the proof mass within a rectangular cavity that measures 1 mm of width by 1.5 mm of length.

When the system vibrates at frequency below 60 Hz, the micro-ball freely moves within the cavity and impact on the upper and lower inner wall of the holed proof mass. Each collision provides a wideband mechanical impulse to the proof mass of the gap-closing comb transducer that in turns resonates at its natural frequency of 92 Hz. In this way, kinetic energy of the input vibration is transferred from 10-60 Hz to higher frequencies in the range of 92-120 Hz. The operation bandwidth of such a mechanical frequency-up conversion depends on the ball travelling distance and on the deflection height of the stopper beams. The cavity length of this first prototype is designed such that the maximum rate of impacts occurs around 15-20 Hz for a given acceleration of 0.3 g (where $g=9.81 \text{ ms}^{-1}$). Based on calculations on the system model, a length of the ball cavity of 7 mm would

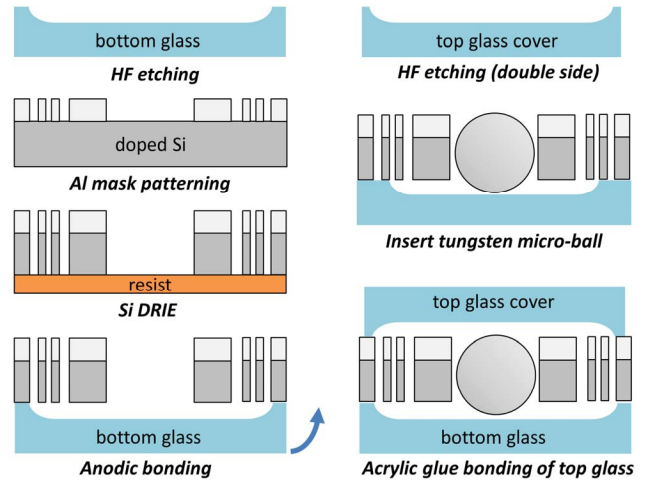


Figure 3: Batch fabrication process of the MEMS-eVEH with the tungsten micro-ball and top glass cover. The support glass was assembled through anodic bonding while the top cap was successively glued with acrylic glue.

optimize the harvester for operation at 2 Hz. This configuration has a great potential for capturing energy from human movements. This is useful, for example, to recharge the battery of a pacemaker.

The fabrication process is shown in figure 3. The structure is obtained by DRIE through a 400- μm -thick silicon wafer, which is then sandwiched between two glass wafers: a support bottom glass and a cover glass that prevents the micro-ball to escape. Anodic bonding assembles the support glass, the micro-ball is then inserted and the top glass realized with double side mask process is subsequently attached with acrylic glue. Silicon beams (60- μm -thick, 2 mm of length) realized in correspondence of the stoppers allow quite good elastic impact of the mass with the rigid frame. The calculated equivalent spring stiffness of the stopper beams at midpoint results $k_{st} = 2.71 \times 10^4 \text{ N/m}$, considering trapezoidal section like in [12] while the stiffness of the serpentine springs along the moving direction results $k_{sp} = 2.10 \text{ N/m}$. The overall die surface measures about $10 \times 10 \text{ mm}^2$. The comb fingers have a length of 2 mm, width of 30 μm and an initial gap g_0 of 70 μm is in between. Table 1 shows the system parameters.

EXPERIMENTAL SETUP

The harvesting device prototype was tested onto an electromagnetic shaker that provided the vibrations (TMS, model K2007E01 with integrated power amplifier). The vibration input was generated and handled by a vibration controller (Brüel & Kjær) through the feedback of an accelerometer. The micro electrostatic VEH was pre-charged at constant voltage V_0 (5-20 V) and the output power is dissipated across a variable load resistance R_L (1 k Ω –0.5 M Ω) connected in series.

Table 1: Model parameters for the VEH prototype.

Parameters	Value
Proof mass, m_s	57.2×10^{-6} Kg
Serpentine springs stiffness, k_{sp}	2.1 Nm^{-1}
Mechanical resonance, f_r	92 Hz
Tungsten micro-ball mass, m_b	4.19×10^{-6} Kg
Stopper beams stiffness, k_{st}	$2.71 \times 10^4 \text{ Nm}^{-1}$
Active area, A_0	$10 \times 10 \text{ mm}^2$
Gap between fingers, g_0	70 μm
Optimal load resistance, R_{opt}	5.6 Mohm
Device thickness, t_d	400 μm
Fingers length, l_f	2 mm
Fingers width, w_f	30 μm

All the signals are then recorded through a data acquisition card (National Instruments, model USB-6211) handled with a PC with a LabView program.

The MEMS e-VEH prototype was initially characterized with both simulations and experimental testing for identifying the model parameters that are listed in Table 1. Subsequently, preliminary tests under sine sweeping for input acceleration $a_i = 0.3g$ rms and different bias voltage $V_0 = 5-20$ V were performed. All the measurements were carried out comparing the system behaviour both with and without the tungsten micro-ball.

RESULTS AND DISCUSSION

Frequency sweeping

Figure 4(a) and (b) display the output RMS voltage and the corresponding harvested power respectively across the optimal load resistance (5.6 M Ω) under frequency up- and down-sweep over 10-120 Hz. The comparison concerns the performance of the MEMS-eVEH prototype with and without the tungsten micro-ball in order to analyze the effect of the mechanical frequency multiplication. In this case, the used bias voltage was $V_0 = 15$ V. Since the support serpentine springs were very soft (2 N/m), above 20 V electrostatic pull-in was observed. Nevertheless, at this voltage level and at 0.3 g of acceleration the micro-ball collision were sufficiently strong to avoid permanent sticking of the parallel plates of the comb capacitor. It is important to notice that the system with micro-ball shows an extended response in frequency with respect to that without it. In particular, the -3db bandwidth increases up to 56% and in the intervals of 10-20 Hz and 40-60 Hz, a significant power enhancement (10 to 100 times) is shown. Most of all it shows to be capable of operating below 20 Hz producing a respectable output power around 0.2 μW with only 15 V of bias voltage. On the other hand, it is interesting to observe that the system without the micro-ball presents a multiple band response at both low (20-50 Hz) and high frequency ranges (90-100 Hz). This effect is due to the repeated bouncing of the proof mass when it collides to the elastic beams of the rigid frame, in correspondence to the stoppers, thanks to the very soft

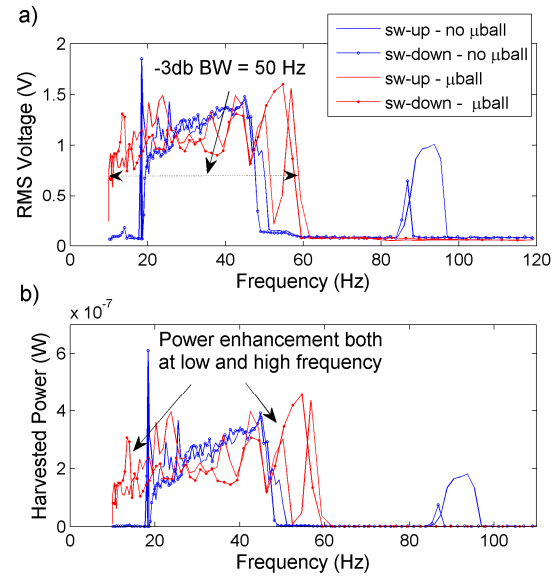


Figure 4: (a) RMS Voltage and (b) harvested power at acceleration amplitude of 0.3 g under sinusoidal frequency up- and down-sweep (10-120 Hz). The comparison regards the same structure with and without the tungsten micro-ball.

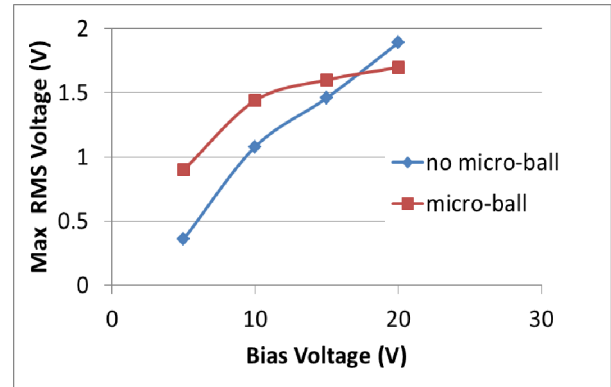


Figure 5: Maximum output voltage across the optimal load $R_l=5.6\text{Mohm}$ on frequency sweeping for the device with and without micro-ball.

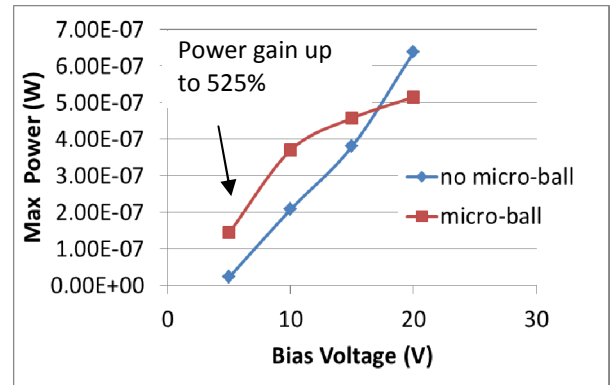


Figure 6: Maximum output harvested power over the optimal load $R_l=5.6\text{Mohm}$ on frequency sweeping for the device with and without micro-ball.

serpentine springs.

Figures 5 and 6 respectively show the maximum output voltage and the harvested power across the optimal load resistance versus the given bias voltage respectively with and without the tungsten micro-ball inside the oscillating mass. It is relevant to observe that for bias voltage lower than 20 V the system with the micro-ball exhibits a power gain of 77.8% at $V_0=10$ V up to 525% at $V_0 = 5$ V. This concept is thus suitable for improving the power harvesting performance when using low voltage external sources to pre-charge the generator (i.e. with PVDF piezoelectric systems). In principle, this system could be designed to work at even higher bias voltage up to 100 V in vacuum by choosing stiffer support springs and heavier micro-ball to prevent a low pull-in voltage. Thus the generated power would be potentially of two orders of magnitudes higher (60-100 μ W).

CONCLUSIONS

This work presented the design, fabrication and testing of a new MEMS electrostatic silicon gap-closing comb vibration energy harvester that exploits mechanical frequency amplification by means of micro-ball impacts with the walls of a holed proof mass in combination with elastic bouncing of the mass with the rigid frame. The main objective was to improve the power generation and extend the operating bandwidth of MEMS e-VEHs at very low frequency.

Under harmonic frequency up- and down-sweeping (10-120 Hz) at 0.3 g rms and with different bias voltages ranging in 2.5-20 V, the electrostatic generator shown a gain factor up to 525% at 5 V of bias voltage in harvesting energy at 10-40 Hz versus the one without the ball. The -3db bandwidth increased up to 56% and in the intervals of 10-20 Hz and 40-60 Hz. This result make the system suitable even for harvesting energy from human movements.

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 and the Galileo Galileo project No. 28150WA.

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