Electret-Free Micromachined Silicon Electrostatic Vibration Energy Harvester With the Bennet's Doubler as Conditioning Circuit

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***Abstract*— This letter presents for the first time experiments combining a previously reported microelectromechanical system electrostatic vibration energy harvester (e-VEH) and the Bennet's doubler circuit. A self-limiting effect on the harvested power, which was not reported before on macroscopic e-VEHs, has been observed. This effect is due to the nonlinear dynamics of the system and to the self-increase of the electromechanical damping that is typical for e-VEHs. With a few volts of initial precharge, the Bennet's doubler progressively increases the voltage across the transducer's terminals up to 23 V, where saturation occurs. A power of 2.3 μW is available for a load, when the harvester is excited by 1.5 g at 150 Hz of external acceleration.**

***Index Terms*— Energy harvesting, Bennet's doubler, MEMS, electrostatic transduction.**

I. Introduction

CURRENTLY, wireless autonomous sensors are considered as key enabling technologies for the creation of a "smart" environment: miniaturization and small energy requirements are the main features of these systems. Microscale devices harvesting energy from the ambient vibrations, or vibration energy harvesters (VEHs), are among the main candidates for energy sources of wireless autonomous sensors.

VEHs are usually based on piezoelectric, electromagnetic or electrostatic energy conversion between mechanical and electrical domains. Electrostatic VEHs (e-VEHs) are usually fabricated with MEMS (silicon micromachining) technology, and are highly compatible with miniaturization and batch fabrication requirements.

In e-VEHs, the conversion of mechanical energy into electrical energy is performed by a mechanical attraction force generated from a charged variable capacitor, which opposes the motion of the mobile electrode of this capacitor. An electret layer or a transducer's pre-charge with a dedicated power source and conditioning circuit is required to generate an appropriate bias generating such force. The power of the energy conversion is proportional to the square of the quantity of charges on the capacitor plates. Generally, a voltage of at least a few tens of volts is required in order to efficiently convert vibrations into electricity. Without using an electret layer, such a high voltage can hardly be provided by an embedded source, and should be generated by the conditioning circuit itself.

To generate a high voltage biasing, most conditioning circuits described in the literature contain in their structure an inductive DC-DC converter [2], whose operation is related to the use of an externally controlled switch requiring a relatively complex control scheme.

Recently published, a conditioning circuit based on Bennet's doubler has generated high voltage biases without the use of any external controllable switch or inductor [3]–[5]. To date, its operation has only been proven with macroscale variable differential capacitors (multiple capacitors varying synchronously with opposite phases), whose variation was induced by an external motor. However, practical e-VEHs are implemented in MEMS technologies [6]. The use of a practical MEMS device (a microresonator along with a capacitive transducer) induces strong electromechanical coupling, which can drastically alter the system's operation [3].

This letter presents results of the first experimental study of an e-VEH based on a Bennet's doubler and a monophasic (single) silicon-MEMS resonant variable capacitor. In section II, the operation principle of the circuit is briefly described and in section III the experimental results are presented.

II. System Description

A. Components of the System

The conditioning circuit of an e-VEH based on Bennet's doubler with a single variable capacitor is shown in Fig. 1. It consists of a large reservoir capacitor (C_{res}), three diodes (D_{1-3}), a fixed capacitor (C_{store}) and a variable capacitor (C_{var}) representing the transducer, associated with a mechanical resonator. Capacitance values are related such that $C_{var} \ll C_{store} \ll C_{res}$. During the conversion process, the converted energy is accumulated into C_{res}, which could supply a load represented here by a resistance (R_{load}). The capacitor C_{res} has to be initially charged to some

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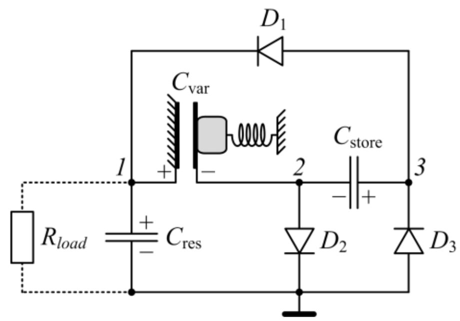

Fig. 1. Vibration energy harvester circuit based on Bennet's doubler with one variable capacitor.

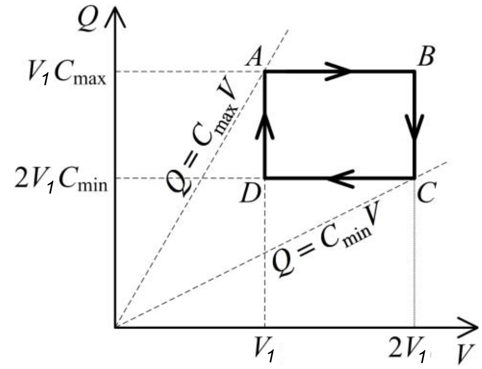

Fig. 2. QV-diagram of the harvesting cycle when $V_1 = V_{init}$: AB and CD: diodes are blocked, DA: D_1 is ON, BC: D_3 is ON.

voltage (V_{init}), whose minimal value depends on the transducer and the circuit elements.

B. Principle of Operation During Start-Up Stage

Initially, both C_{var} and C_{store} are discharged, $V_1 = V_{init}$, and C_{var} is at its maximum value. Immediately, C_{var} charges through the diode D_2 (D_1 and D_3 are OFF), whereas C_{store} is still discharged. Since C_{res} is significantly larger than the other capacitances, V_1 can be considered constant during one cycle of operation. As C_{var} decreases because of the vibrations, its voltage increases making V_2 negative and D_2 OFF. The voltage V_3 also decreases down to the diode threshold V_{th}, then D_3 becomes ON and C_{store} starts to charge through D_3.

When C_{var} increases again, V_2 increases until D_2 is ON, D_3 is OFF and C_{var} compensates the charges it has given to C_{store} with charges coming from C_{res} through D_2. This process repeats until the charge Q_{2_init} on node 2 is given by:

$$Q_{2\_init} = Q_{Cmax} + Q_{store} \approx C_{max}(V_{th} - V_1) - C_{store}V_1. \quad (1)$$

C. Principle of the Charge Accumulation on C_{res}

The conversion of mechanical energy into electricity can be understood if one considers the circuit under the following assumptions: (i) the reservoir capacitor C_{res} is pre-charged to some voltage V_{init}; (ii) the diode D_2 remains OFF because of the negative charge Q_2 initially injected in node 2 during the start-up stage; (iii) Q_2 is constant during one conversion cycle.

During the variation of C_{var}, Q_2 is continuously redistributed between C_{store} and C_{var}. Since Q_2 is negative, the opposite plate of C_{store} at node 3 has a positive charge. When D_1 and D_3 are OFF, the C_{store} current is zero. At the same time, the voltage of node 3 (V_3) alternates between $-V_{th}$ and $V_{th} + V_1$ because of C_{var} variation. When D_3 is ON, the charges accumulate at node 3 (flowing from the ground) while C_{var} decreases. When D_1 is ON, positive charges flow out from node 3 while C_{var} increases. In this way, node 1 receives positive charges at each cycle. Since no mechanism allows a loss of positive charges on node 1, the voltage V_1 can only increase slightly at each cycle. This happens when D_3 becomes ON and C_{res} receives charges from both C_{var} and the electrical ground.

The increase of V_1 results in an increase of Q_2 with additional charges on node 2 coming from D_2 at each cycle (as in the start-up stage). Hence, there are two key roles of D_2. Firstly, it brings the initial charge Q_{2_init} to node 2. Secondly, it updates the Q_2 value according to Eq. 1 as V_1 increases (V_{init} is replaced by the actual value of V_1). It can be shown that the amount of charges passing through D_2 is a few orders of magnitude lower than the amount of charges passing through D_1 and D_3 over one C_{var} variation period (cf. the above assumption of constant charge of node 2).

The QV-diagram presented in Fig. 2 shows the relationship between variable capacitor charge Q_{var} and its voltage in a steady-state operation when $V_{th} = 0$. Point A corresponds to the state when C_{var} is maximal; point C corresponds to the state when C_{var} is minimal; points B and D correspond to the states at which diodes D_3 and D_1 switch ON, respectively. The cycle area $ABCD$ is equal to the energy converted by the transducer during one operation cycle, which is defined by one C_{var} variation period. This energy can be estimated by the expression:

$$W_{cycle} = V_1^2 C_{max}\,(1 - 2/\eta) \quad (2)$$

where $\eta = C_{max}/C_{min}$.

At each cycle, a part of W_{cycle} is lost in the diodes and the remaining part is reinvested in C_{var} and C_{store}, as pointed out previously. The remaining energy (ΔW_{res}) is gathered in C_{res}. It is notable that Eq. 2 is only positive when the condition $\eta > 2$ is true. Otherwise, the voltage variation on the variable capacitor is not large enough to modify the states of the diodes, and the circuit will not operate in the energy conversion mode. The strong requirement of $\eta > 2$ is often difficult to fulfill with MEMS transducers. However, it can be shown that this condition is related to the charge Q_2 on node 2, defined by the diode D_2. By modulating this charge, energy conversion is possible for lower η, but with slightly different circuit topology.

III. Experiments

The experiments were carried out using a $12 \times 10 \times 0.4$ mm^3 MEMS resonant variable capacitor. The resonator's unbiased resonance frequency was 160 Hz, with a quality factor of 8.5 in air. The utilized MEMS capacitor is shown in Fig. 3. Its main characteristics and fabrication technique were similar to those previously described [6]. It was made in a silicon-glass batch process. It had gap-closing interdigitated-comb electrodes moving in-plane. The measured unbiased transducer capacitance variation ratio induced by harmonic vibrations of 1.5 g amplitude at 150 Hz frequency was: C_{max}/C_{min} = 124 pF / 46 pF ($\eta = 2.7$).

The measured voltage evolution on C_{res} = 100 nF at several frequencies and amplitudes of external acceleration

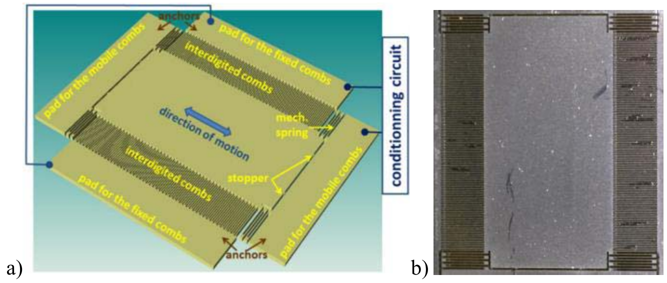

Fig. 3. (a) Three-dimensional schematic view of the variable capacitor device; (b) photograph of the variable capacitor device.

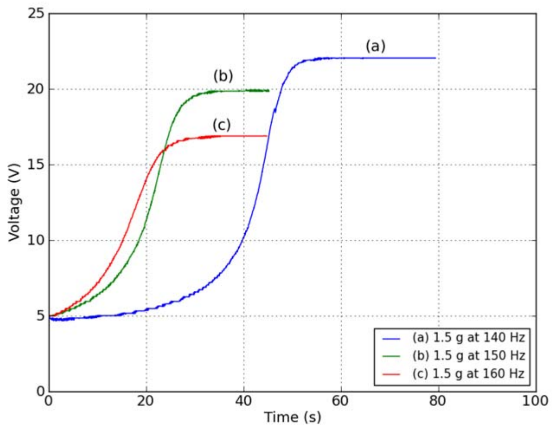

Fig. 4. Measured evolution of voltage across C_{res}, for several input acceleration frequencies of 1.5 g amplitude.

($C_{store} = 1.5$ nF) are shown in Fig. 4 and Fig. 5, respectively. At time $t = 0$, C_{res} is charged to $V_{init} = 5$ V.

The increase of the voltage across C_{res} corresponds to an increase of the accumulated energy. At first, an exponential (avalanche) increase was observed: according to Eq. 2, the energy accumulation rate is proportional to V_1^2, which itself is proportional to the accumulated energy. However, after several cycles of conversion, the voltage ceased to increase, eventually leading to saturation. Thus, for each input, a voltage exists at which the harvested power is maximal. The maximal obtained power on C_{res} was 2.3 μW, at 16.5 V. At this voltage, both circuit analysis and simulation provided a ratio $\Delta W_{res}/W_{cycle}$ near 94%, the dominant source of losses being the Joule dissipation in the diodes D_1 and D_3. This gave a measured W_{cycle} of 2.5 μW. For the same voltage, the uncoupled model predicts $W_{cycle} = 2.6$ μW (cf. Eq. 2 with $\eta = 2.7$).

The saturation of the voltage across C_{res} was not observed in a previous experiment [3] where a macroscopic capacitor was used. This saturation phenomenon is due to the electromechanical coupling. Indeed, the resonance frequency of the harvester decreased with its increasing biasing by the conditioning circuit, and the input frequency was not anymore in the mechanical system bandwidth for large V_1 [6]. This was confirmed by the results shown in Fig. 4: excitations at lower frequencies slowly increased the voltage across C_{res} because of their distance from the unbiased resonance frequency, but led to an ultimately higher saturation voltage. In addition, the increasing electromechanical damping reduced the transducer's movement amplitude at all frequencies. This, along with the resonance frequency shift, is why larger input amplitudes led to faster increase and higher voltages,

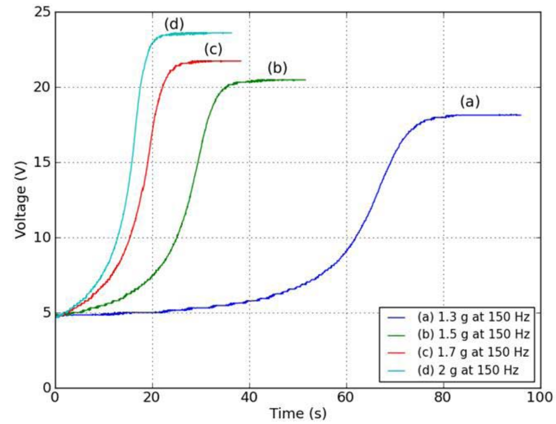

Fig. 5. Measured evolution of voltage across C_{res}, for several input acceleration amplitudes of 150 Hz frequency.

as depicted in Fig. 5. These phenomena cause the decrease of η, until η is such that $\Delta W_{res} = 0$. Hence, the fundamental law on maximal power in VEH is enforced: only a limited amount of energy can be converted from a mechanical resonator at given external vibrations [6].

IV. Discussion and Conclusion

This letter presents the first experiments of a vibration energy harvesting system including a MEMS e-VEH and a circuit of the family of Bennet's doublers. These kinds of conditioning circuits do not require any switches or inductors. Moreover, they have a self-increasing polarization of the electrostatic transducer once a low-voltage pre-charge has been applied.

A converted power of 2.3 μW was obtained at 1.5 g for a variable capacitance ratio of $\eta = 2.7$. This was in good agreement with what was observed previously [6], where 2.2 μW was obtained at 1 g with a similar device having $\eta = 2$ and a continuous conditioning circuit with a bias voltage of 30 V.

This letter highlights specific effects related with microscale electromechanical coupling, such as the sensitivity of the level of converted energy regarding the voltage across the C_{res} capacitor. For this reason, in practice, an intelligent power management is required to interface the presented circuit with a load, requiring a normalized low power voltage [3].

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