Characterization of the capacitance variation of electrostatic vibration energy harvesters biased following rectangular charge-voltage diagrams

Armine Karami, Dimitri Galayko, Philippe Basset

Characterization of the capacitance variation of electrostatic vibration energy harvesters biased following rectangular charge-voltage diagrams

Armine Karami[1], Dimitri Galayko[1], Philippe Basset[2]
[1]Sorbonne Universités, UPMC Univ Paris 06, UMR 7606, LIP6, F-75005 Paris, France
[2]Université Paris-Est, ESYCOM, ESIEE-Paris, 93160 Noisy-Le-Grand, France

E-mail: armine.karami@lip6.fr

Abstract. This paper presents for the first time a method to measure the capacitance variation of electrostatic vibration energy harvesters (e-VEHs) that employ conditioning circuits implementing a biasing scheme that can be represented by a rectangular charge-voltage diagram. Given the increasing number of e-VEHs using such complex conditioning circuits and the complex dynamics that are induced from this type of biasing, a mean to assess this measurement is of primary importance for the analysis of e-VEHs. The proposed method is based on the inspection of the voltage evolution across two simple conditioning circuits implementing a rectangular charge-voltage diagrams biasing scheme. After the method is presented, it is carried out for the characterization of a state-of-the-art MEMS e-VEH.

1. Introduction

Recent research on micro-machined electrostatic vibration energy harvesters (e-VEHs) have shown that the electrical conditioning and load interfacing part of such systems is critical to the performances in terms of harvested power. In the light of this consideration, researchers have started to investigate new types of conditioning circuits [1, 2, 3]. These new conditioning circuits have in common that their biasing of the transducer, across one cycle of its capacitance variation, can be summarized by a rectangular charge-voltage characteristic diagram (QV diagram) [4].

However, the way this type of biasing affects the device's dynamics via the electromechanical coupling effect is still unclear: although semi-analytical approximations are possible for a limited range of input conditions [5], no measurement method allowed to measure the electromechanical coupling effect on the dynamics of a given e-VEH. In particular no method was reported for the measurement of the extremal values of capacitance variation for a device submitted to harmonic input excitation and biased following a rectangular QV diagram.

In this paper, a simple method is proposed to carry out such a measurement. This method only involves the use of characterization equipment that is typically found in MEMS e-VEHs characterization labs, i.e., generic electronics components, characterization gear, and a mechanical shaker. This method is based on the dynamics of two simple circuits implementing biasing schemes described by rectangular QV diagrams. After a brief presentation and analysis of these circuits, the method is presented and carried out as an example on a state-of-the-art micro-machined, symmetrical gap-closing geometry e-VEH.

2. Presentation of the circuits used for the characterization

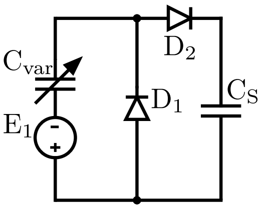

Figure 1. First conditioning circuit used for the characterization of C_{max} and C_{min}.

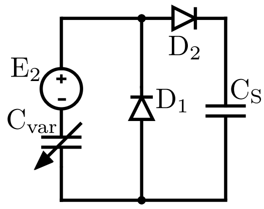

Figure 2. Second conditioning circuit used for the characterization of C_{max} and C_{min}.

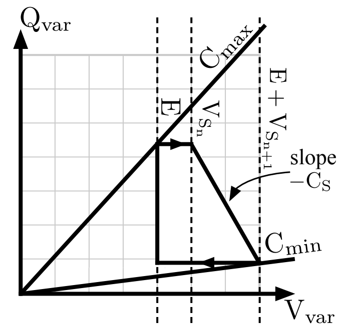

Figure 3. QV diagram for the circuit depicted in Fig. 1.

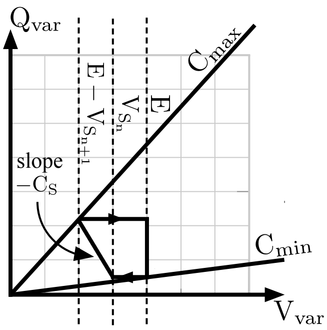

Figure 4. QV diagram for the circuit depicted in Fig. 2.

Consider the two conditioning circuits depicted in Fig. 1 and Fig. 2. The voltage source elements E_1 and E_2 model external voltage sources, eventually superposed with the effect of electret charging. The QV diagrams of the corresponding circuits are depicted in Fig. 3 and Fig. 4. The diodes are supposed to follow an ideal diode voltage-current law, with threshold voltage $V_T \geq 0$. Defining a variation cycle by the transducer's variable capacitance varying from a maximal value C_{max} to a minimal value C_{min} and then from C_{min} to C_{max}, it comes for the local evolution laws of each of the circuits that:

$$V_{n+1}^{\#1} = \frac{C_S V_n^{\#1} + (C_{max} - C_{min})E_1 - (C_{max} + C_{min})V_T}{C_{min} + C_S}, \tag{1}$$

$$V_{n+1}^{\#2} = \frac{C_S V_n^{\#HW2} + (C_{max} - C_{min})E_2 - (C_{max} + C_{min})V_T}{C_{max} + C_S}, \tag{2}$$

where $V_n^{\#1}$ and $V_n^{\#2}$ denote the value of the voltage across C_S at cycle index n for the circuits depicted in Fig. 1 and Fig. 2, respectively.

3. Presentation of the measurement method

From the preceding equations, denoting $\Delta_1 = V_{n+1}^{\#1} - V_n^{\#1}$, $\Delta_2 = V_{n+1}^{\#1} - V_n^{\#1}$, $V_1 = V_n^{\#1}$ and $V_2 = V_n^{\#2}$, it comes:

$$C_{min} = C_S \frac{\Delta_2(E_1 - V_T) - \Delta_1(E_2 - V_T - \Delta_2 - V_2)}{(E_1 + \Delta_1 + V_1 + V_T)(E_2 - \Delta_2 - V_2 - V_T) - (E_1 - V_T)(E_2 + V_T)}, \tag{3}$$

$$C_{max} = \frac{C_S \Delta_2 + C_{min}(E_2 + V_T)}{E_2 - V_2 - \Delta_2}. \tag{4}$$

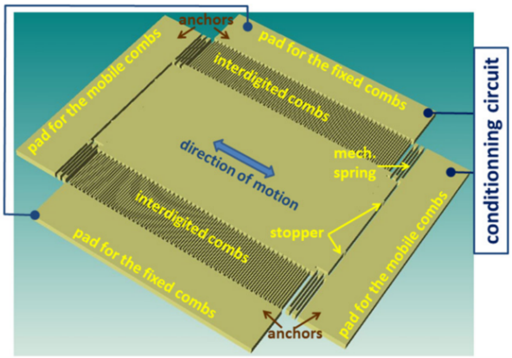

Figure 5. 3D schematic of the MEMS transducer that is characterized as an example of application of the presented measurement method.

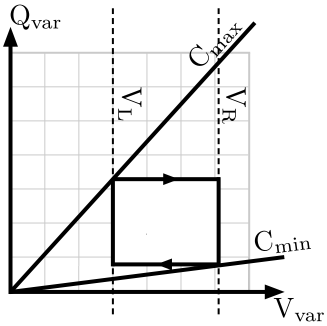

Figure 6. Generic rectangular QV diagram, with extreme voltages V_L and V_R.

Let's consider an e-VEH for which the value of maximal capacitance C_{max} is to be measured, when the device is submitted to an harmonic external excitation, and when its biasing across one cycle of variation is described by a rectangular charge-voltage diagram of extremal voltages V_L and V_R (see Fig. 6). Suppose the slope of the non-horizontal portions of the QV cycles of the two conditioning circuits is large compared to C_{max}, i.e., $C_S \gg C_{max}$ (see Fig. 3 and Fig. 4). By choosing the values of the external voltages sources and initial voltages across C_S such that:

$$E_1 = V_L, \tag{5}$$
$$E_2 = V_R, \tag{6}$$
$$V_1 = V_2 = V_R - V_L, \tag{7}$$

it comes that evaluating (3) and (4) with the values of Δ_1 and Δ_2 measured with these parameters yields the values of C_{max} and C_{min} as affected by the electromechanical coupling induced by the rectangular biasing depicted in Fig. 6.

Note that the values of C_{max} and C_{min} result from a dynamical process, and hence the measurement method is accurate only if the electromechanical coupling impact on the e-VEH's dynamics can be considered as a quasi-static process: otherwise, a systematic error is introduced in the measurement. This hypothesis is verified if C_S is chosen such that the values of Δ_1 and Δ_2 do not change abruptly from one cycle to the next, i.e., that C_S is chosen large enough. Also, this results in the QV diagrams in Fig. 3 and Fig. 4 to become more alike, which improves the measurement accuracy. However, a too large value of C_S results in Δ_1 and Δ_2 becoming indiscernible one from another because of a non-null noise floor due to random noise sources. Thus, prior to the measurement, a study should be done to chose the optimal value for C_S given those constraints.

4. Example of transducer characterization using the presented method

As an illustrating example, the following describes the application of the method to the measurement of the value of C_{max} for a practical transducer, that has been previously reported in [6]. The schematic of the transducer is depicted in Fig. 5. The measurement is carried out for the transducer biased following a rectangular QV diagram, with $V_L = 10$V and $V_R = 15$V, and mechanically forced by an external excitation of 1.5g amplitude, 150Hz frequency. Because of the symmetrical gap-closing geometry of the device, the value of C_{min} is fixed throughout

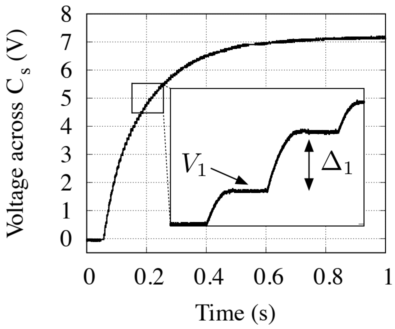

Figure 7. Complete time-evolution of the voltage across C_S for the circuit depicted in Fig. 1, with $E_1 = 10$V, with the transducer submitted to input acceleration of 1.5g amplitude at 150Hz frequency. The quantities V_1 and Δ_1 are highlighted.

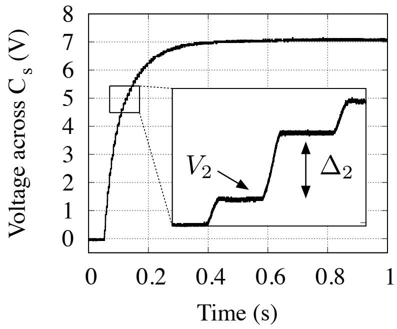

Figure 8. Complete time-evolution of the voltage across C_S for the circuit depicted in Fig. 2, with $E_2 = 15$V, with the transducer submitted to input acceleration of 1.5g amplitude at 150Hz frequency. The quantities V_2 and Δ_2 are highlighted.

the e-VEH's operation, and is measured by standard capacitance measurement means, as $C_{min} = 55$pF. In both circuits, the fixed capacitor is chosen such that $C_S = 500$pF.

Because C_{min} is fixed, only the circuit in Fig. 2 is necessary. The parameters for the measurements are $E_2 = 15$V, and $V_2 = 5$V (see (6) and (7)). Several measurements are carried out for the characterization, with approximatively equal values of V_2, to statistically estimate the uncertainty due to type A error sources on the measurements. With the obtained results for (Δ_2, V_2), applying (4) yields a value of $C_{max} = 94.7\text{pF} \pm 2.8\text{pF}$.

Equation (3) can be used to check the results as C_{min} is fixed, by carrying out the same measurement with the circuit in Fig. 1, choosing $E_1 = 10$V, and at $V_1 = 5$V (see (5) and (7)). If the geometry of the device is such that C_{min} is not unalterable, this latter measurement has to be carried out to measure the value of C_{min} as impacted by the electromechanical coupling resulting from the bias depicted in Fig. 6.

5. Conclusion

This work presented the first method to measure the capacitance variation of electrostatic MEMS transducers of an e-VEHs, when electrically conditioned following a rectangular charge-voltage diagram. This enables more thorough studies on the effect of the electromechanical coupling on the dynamics of e-VEH using electrical interfaces implementing these types of conditionings schemes, such as charge-pump conditioning circuits.

6. References

[1] De Queiroz A C M 2014 *2014 IEEE 5th Latin American Symposium on Circuits and Systems* 1–4

[2] Karami A, Galayko D and Basset P 2016 *IEEE Transactions on Circuits and Systems I: Regular Papers* **PP** 1–14 ISSN 1549-8328

[3] Wei J, Risquez S, Mathias H, Lefeuvre E and Costa F 2015 Simple and efficient interface circuit for vibration electrostatic energy harvesters *SENSORS, 2015 IEEE* pp 1–4

[4] Galayko D, Dudka A, Karami A, O'Riordan E, Blokhina E, Feely O and Basset P 2015 *IEEE Transactions on Circuits and Systems I: Regular Papers* **62** 2652–2663

[5] O'Riordan E, Dudka A, Galayko D, Basset P, Feely O and Blokhina E 2015 *IEEE Transactions on Circuits and Systems I: Regular Papers* **62** 2664–2673

[6] Lu Y, ORiordan E, Cottone F, Boisseau S, Galayko D, Blokhina E, Marty F and Basset P 2016 *Journal of Micromechanics and Microengineering* **26** 124004