Power Extraction from Ambient Vibration

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Abstract — **Autonomous devices such as sensors for personal area networks need a long battery lifetime in a small volume. The battery size can be reduced by incorporating micro-power generators based on ambient energy. This paper describes a new approach to the conversion of mechanical to electrical energy, based on charge transportation between two parallel capacitors. The polarization of the device is handled by an electret. A large-signal model was developed, allowing simulations of the behavior of any circuit based on this generator for any mechanical input signal. A small-signal model was derived in order to quantify the output power as a function of the design parameters. A layout was made based on a standard SOI-technology, available in a MPW. With this layout it is possible to generate 100 μW at 1200 Hz.**

Keywords — **power, generator, MEMS, electret**

I. INTRODUCTION

As miniaturization of electronic circuits proceeds, their applications reach sizes and weights suitable for autonomous and portable uses, creating a demand for small, lightweight energy-supplies with high energy densities. The use of a battery causes problems if replacing or recharging the battery is difficult or impossible (such as for implanted and distributed systems). A solution consists in using small generators extracting energy from the environment, so only a time-buffering battery will be needed.

Environmental energy can be solar, thermal, kinetic, chemical, acoustic or electrical. Conversion and conditioning to an applicable electrical form is performed by a generator system [1] allowing a theoretically infinite lifetime.

Earlier work on vibrational energy scavenging based on electromagnetic [2-5], electrostatic [6,7] or piezoelectric [8,9] conversion illustrates the great interest in micro-generators for applications where battery-replacement is unacceptable and kinetic energy is amply available [10,11]. This paper describes a new approach to electrostatic converters. The generator is based on charge transportation between two parallel plate capacitors, and on the use of a charged dielectric (*electret*) as polarization of the electrostatic converter.

II. DEVICE CONCEPT

The device consists of two parallel capacitors, one of a constant capacitance C_1, the other of a variable capacitance C_2, carrying a constant charge Q (Fig. 1). The parallel connection distributes this charge Q proportionally over the capacitors, into a charge Q_1 on C_1 and a charge Q_2 on C_2 as indicated by (1) :

$$Q_1 = \frac{C_1}{C_1 + C_2} Q \qquad Q_2 = \frac{C_2}{C_1 + C_2} Q \qquad (1)$$

By changing the capacitance C_2 to $C_2+\Delta C$, but keeping the charge Q constant, the charge Q_1 increases by the same amount ΔQ as the charge Q_2 decreases, indicating a charge transport through an external circuit :

$$\Delta Q = \frac{C_1 \Delta C}{(C_1 + C_2 + \Delta C)(C_1 + C_2)} \qquad (2)$$

The charge transport gives rise to a current, which supplies energy to an external circuit (represented by the resistance R). This energy originates from the mechanical vibrations responsible of the capacitance change.

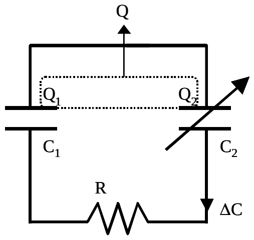

Figure 1 : Working principle of the energy converter

A schematic view of the device that we have designed is given in Fig 2. It consists of a combed in-plane variable capacitor and of a seismic mass (sensitive to acceleration), mechanically connected to the movable electrode (electrode A). The change in geometry caused by the movements of the mass relative to the housing, changes the capacitance between the electrodes. The constant charge Q is realized by an *electret*, i.e. a fixed charge distribution in a dielectric material. The device can be easily fabricated with the use of MEMS-technology. The results of simulations shown further will be based on this design.

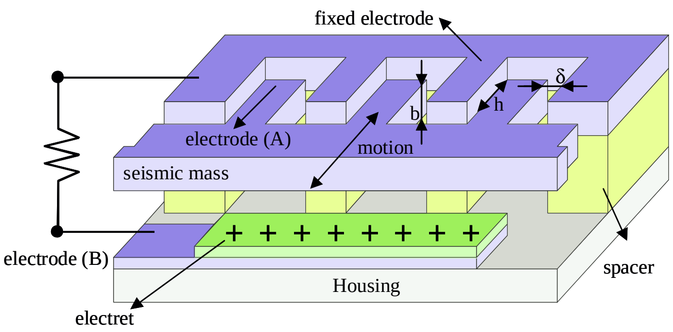

Figure 2 : Cross-section of a MEMS-based vibration-to-electric generator

The micromachined capacitor has been doubled into two variable capacitors with opposite capacitance-variations (See schematics of Fig. 3). In this way the charge transport to the common electrode of the capacitors (electrode A) is zero, reducing energy losses due to internal resistivity.

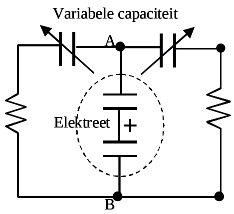

Figure 3 : Working principle of doubled variable capacitor

Previous studies on electrostatic energy conversion [6,7] use the increase of the energy stored in the variable capacitor. After this increase, the capacitor is discharged in the load. The charging still requires an incorporated battery and a charging circuit, while the duty cycle is only 50%.

The use of an electret for polarization and the charge transportation method used in this paper allow a 100% duty cycle, and no initial battery is needed.

III. Large-Signal Modeling

In order to optimize the design towards maximal electrical power for a given vibration, a large signal model of the device was built. It consists of a combination of the large-signal models of the electret and of the variable capacitor.

A. Electret

Any fixed homopolar charge-distribution can be modeled as an equivalent charge-layer at a fixed position [12]. These fixed charges become electrically useful, by applying two electrodes (Fig. 4).

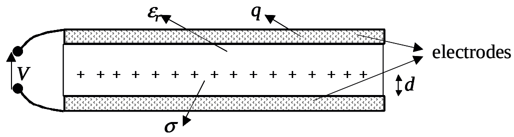

Figure 4 : Homopolar electret

The relationship between the voltage V across the electrodes and the charges q is deducted using Gauss' Law and Faraday's Law for electrostatics. The relationship between V and q is given in (3), with the symbols as defined in Fig. 4 :

$$V = q \cdot \frac{1}{C_{tot}} + \sigma \frac{d}{\varepsilon_0 \varepsilon_r} = q \cdot \frac{1}{C_{tot}} + V_{elec} \qquad (3)$$

The capacitance C_{tot} is the capacitance between the electrodes if no charge-distribution is present, while σ represents the net charge in the distribution.

An equivalent electrical circuit is deducted from equation (3), consisting of a capacitor and a voltage source, allowing simulations of electret-based circuits with circuit-analyzing software, such as SPICE.

In the case of heteropolar fixed charges the analysis proceeds in the same way, except for a different definition of the distance d. The model and its implementation remain valid.

B. Variable capacitor

The large-signal model of the variable capacitor can be deducted from analyzing the energy function of the combed variable capacitor [13], resulting in two relationships between the mechanical parameters, displacement x and external force F_e, and the electrical parameters, voltage V and charge q :

$$\begin{cases} F_e = \dfrac{1}{2}\dfrac{q^2\delta}{2N\varepsilon_0 b(h-x)^2} \\ V = \dfrac{q\delta}{2N\varepsilon_0 b(h-x)} \end{cases} \qquad (4)$$

with :

ε_0	Permittivity of vacuum
N	Number of fingers
b	Height of the fingers
h	Initial overlap of the fingers
δ	Distance between two fingers

The implementation of this equation in SPICE using Verilog-A language gives a two-port component, enabling simulations of electronic circuits with variable capacitors, such as electrostatic actuators. This SPICE model also allows the simulation of current-voltage graphs, similar to those of photovoltaic generators.

IV. SMALL-SIGNAL MODELING

To understand the effect of the design parameters on voltage, power or amplitude as a function of frequency, a linear model was derived, based on the large-signal model.

As the large signal model of the electret is already linear, it can serve as a small signal model. After linearization of equations (4) an electrical equivalent of the variable capacitor can be deduced [14]. To complete the scheme, the electrical equivalents for the mechanical mass, spring and damping were combined with the small-signal models into an electrical equivalent circuit for the generator (Fig. 5). The mechanical input is taken into account by connecting a voltage source (for a force) or a current source (for a displacements velocity) to the connectors.

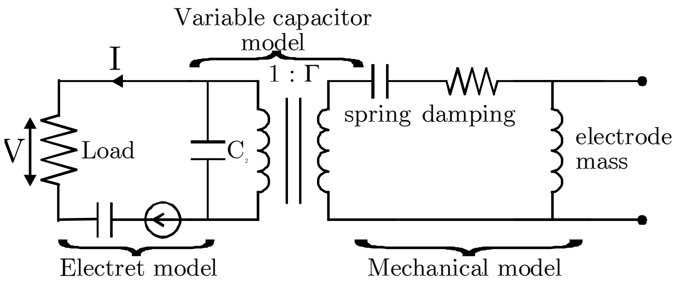

Figure 5 : Equivalent electrical circuit of the linearised variable capacitor (single capacitor, not doubled)

By using standard circuit analyses, the output power of the linearised energy converter is formulated as a function of the pulsation ω and of the amplitude Y of the mechanical source. If damping and resistive losses are neglected, the formula simplifies to:

$$P(\omega) = \frac{\left(\frac{\omega}{\omega_1^*}\right)^4 \left(\frac{\omega}{\omega_2}\right)^2 \frac{\Gamma^2}{C_2^2} \frac{Y^2}{2R}}{\left(\alpha^2 - \left(\frac{\omega}{\omega_1^*}\right)^2\right)^2 + \left(\frac{\omega}{\omega_2}\right)^2 \left(1 - \left(\frac{\omega}{\omega_1^*}\right)^2\right)^2} \quad (5)$$

In this equation ω_1^* is the resonance frequency of the circuit of Fig. 5 with an infinite load. It is higher than the mechanical resonance frequency.

The frequency ω_2 is the cut-off frequency of the filter formed by the load and the two parallel capacitors. The effect of the capacitance C_{tot} on the power is taken into account by α. This factor is always smaller than 1.

The factor Γ represents the increase in charge (μC) on the variable capacitor due to a displacement of one micrometer.

Fig. 6 gives the power spectrum of the designed prototype, for an electret voltage of 100V [15] and for different loads.

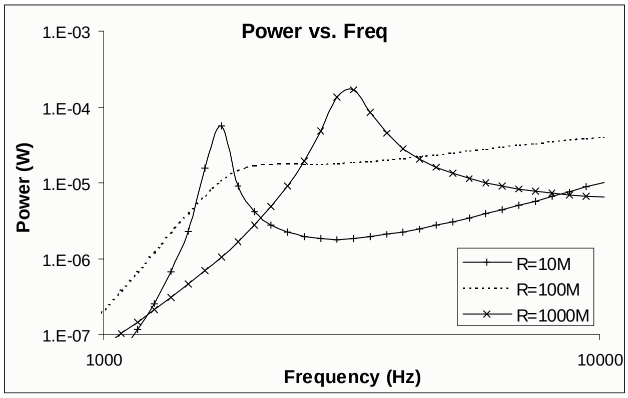

Figure 6 : Power vs. Frequency (parameter = load resistance)

Let's first consider the case of low values of R. The cut-off frequency ω_2 is large and around the resonance frequency the second term in the denominator of (5) can be neglected with respect to the first one. The resonance occurs then at $\alpha\omega_1^*$. The resonance frequency is very close to the mechanical resonance frequency.

With increasing the load, the resonance shifts to the higher frequency ω_1^*. This allows a shaping of the frequency response of the converter by changing the load.

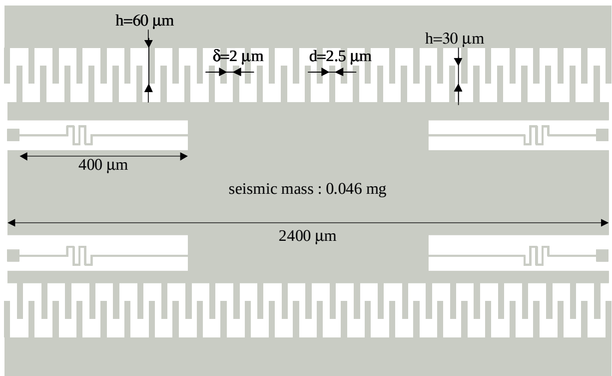

Figure 7 : Schematic overview of the layout

V. REALIZATION

The conceptual design of the device allows a separate fabrication of the electret and of the variable capacitor. As the variable capacitor is a common structure for MEMS-devices such as accelerometers and resonators, the fabrication is done using the MPW-services offered by Tronic's [16]. The layout is shown in Fig. 7. The variable capacitor has a surface of 4 mm^2 and was designed for vibrations of 20 μm. An electret, such as charged SiO_2 layers [15], will be bonded to the housing of the variable capacitor, as indicated by Fig. 3.

VI. DISCUSSION

The implementation of the variable capacitor through MPW offers the opportunity of realizing in a short time span a reliable micromechanical device. Simultaneously the other parts of the generator can be optimized. On the other hand, the design is tied to an existing process, which limits the possibilities for optimization. It turned out to be very hard to realize a low resonance frequency in the given SOI-technology, because of the constraints in mass-depth and minimal spring dimensions.

VII. SUMMARY

A new approach to electrostatic energy conversion has been proposed and modeled. The large signal model allows simulation of any generator-based circuit in any ambient mechanical conditions. A small signal model was used for evaluating the influences of the design parameters on the output characteristics, leading towards the design of a variable capacitor, based on a SOI-process, available in MPW-service. According to this feasibility study, 100 μW electrical power is available at 1200 Hz for a device displacement of only 20 μm.

VIII. ACKNOWLEDGEMENTS

The authors would like to thank Omar A. Nasr for his help in system analysis and spring design, and Paolo Fiorini for revising the layout.

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