

Planar Electret Based Electrostatic Micro-Generator

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Abstract

Development of a planar electret based electrostatic micro-generator for vibration energy harvesting is presented. In order to fabricate an efficient MEMS transducer, a planar implementation is introduced allowing low cost and low power losses operation. Moreover, using a slatted periodic structure allows decoupling between the energy conversion cycle and the vibration source frequency. In this paper, the details of this implementation are revealed. Modeling equations of the resulting structure are illustrated and solved numerically. Simulation results will be given showing more than 78% improvement in the average output power of the optimized structure compared to previous implementation.

Keywords: MEMS, Electrostatic, Electret, Micro-generators, Energy harvesting

1 - INTRODUCTION

Recently, with the advances of integrated circuits and low power applications, it is possible to operate devices with an extremely low power (e.g. biosensors and RFID). Current batteries implementations offer a good solution for these systems when it comes to 1~3 years of operation [1]. However, for life-time operation or embedded sensors applications, batteries or constant energy sources reach their limitation.

As an alternative, energy harvesting from the surrounding environment becomes an appealing power source. This concept deals with harvesting energy from the surrounding energy sources. Vibration-based energy harvesters represent one of these evolving methods. These scavengers or generators fall into one of three categories: piezoelectric, electromagnetic or electrostatic. Electrostatic micro-generators have the advantage of compatibility with current MEMS technology. However, current implementations of the electrostatic energy transducer used for micro-generation suffer from limitations that hinder efficient energy harvesting. Some of these limitations are related to the energy transducer like large mechanical damping of the movable parts, while others are related to the energy conversion process like the need of an electrical source for triggering conversion process and the associated power electronics circuits.

In this paper, A planar electret-based electrostatic micro-generator is introduced which overcomes most of these problems associated with the current implementations. The paper is organized as follows: Section 2 illustrates the theory of operation of the transducer and the limitation of the current implementation. Section 3 presents the alternative planar implementation used to improve the performance. Section 4 deals with the transducer modeling issues. Simulation results

are revealed in Section 5. Finally, conclusions are given in Section 6.

2 - THEORY OF OPERATION

The electrical energy generation in electrostatic micro-generator is performed through a transducer. This transducer is simply one or more charged variable capacitors. The force due to vibration changes their capacitance leading to the change in the amount of stored energy and the flow of charges between them.

As a result, the work done by the vibration energy in varying the capacitance is transformed to electrical energy in one of the two forms: an increase in the stored charges or the capacitors voltages or as a transfer of charge between capacitors and the load in the form of electric current. The first form requires special control circuits to control the conversion cycle and ensure the repeatability of the conversion process as well as power electronics circuits to extract the resulting energy. As a result, the generated energy is limited by the losses in these circuits [2].

In contrast, control circuits are eliminated by using the work done by vibration energy in transferring the charges and thus the passage of current. Figure 1 shows a circuit topology proposed by Sterken *et al* [4] to perform such operation. The two variable capacitors are varying in opposite sense with the vibration. Assuming the similar loads, the charges will go back and forth due to the opposite capacitance variation of the variable capacitors. As a result, an out of phase currents will pass through the loads while negligible current will pass through the constant capacitor due to the symmetry of the circuit.

Moreover, Sterken *et al* has proposed an implementation to this circuit topology using two comb-finger capacitors with

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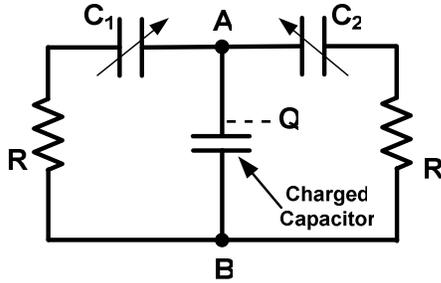


Figure 1– Balanced transducer circuit topology

overlap variation while the charged constant capacitance is implemented by using an electret layer enclosed between the housing substrate and the movable electrode of the comb finger capacitor.

However, such implementation suffers from certain limitations facing the use of variable comb-finger capacitors in the transducers for electrostatic micro-generators. Transducers in electrostatic micro-generators require large nominal capacitance values with large capacitance variation. Such requirement is difficult to achieve in comb-finger capacitors except with large structures and high aspect ratio bulk etching processes like Deep Reactive Ion Etching (DRIE). Moreover, the resulting capacitor will suffer from large parasitic resistance due to the limited conductivity of the silicon substrate where large dimensions are required for large capacitance implementation. Therefore, the resulting micro-generator will be expensive, large in size and inefficient in terms of the power generated.

3 - TRANSDUCER IMPLEMENTATION

As an alternative to solve the above problems, a new planar implementation to the transducer circuit topology is introduced. To overcome the problem of limited conductivity of the capacitor electrodes, parallel plate electrodes are used allowing the use of metallic electrodes. Moreover, the limited variation inherited in in-plane variable parallel plate capacitor is improved by cutting the electrodes into slabs. Such modification increases the theoretical variation range of the variable capacitor. In addition, dividing the variable capacitor into slabs leads to the occurrence of multiple maxima and minima during one mechanical vibration cycle. Therefore, the electrical conversion cycle occurs multiple of time in a mechanical vibration cycle leading to increase in the amount of generated power.

Figure 2 illustrates a 3D schematic of the new implementation and a cross section of the structure showing the relative position of the slabs with respect to each other allowing opposite variation of the two variable capacitors.

4 - TRANSDUCER MODELING

Mathematic modeling of the new proposed implementation encloses modeling of the different component of the transducer: enclosed electret, and the variable capacitor.

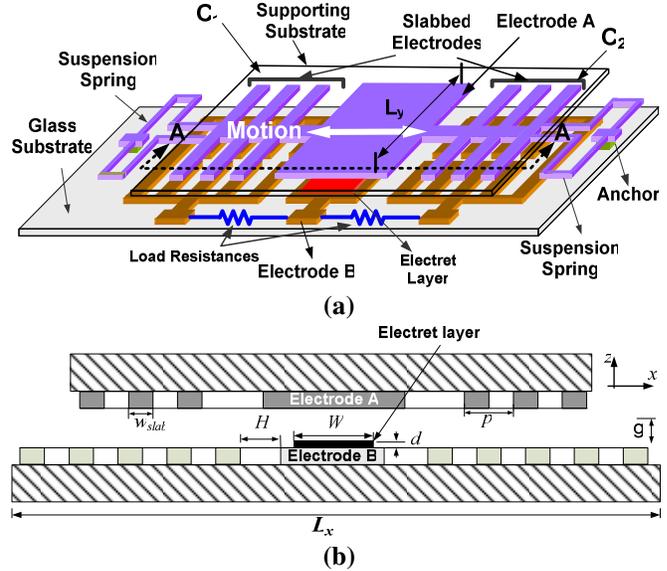


Figure 2 – The planar implementation of the electrostatic transducer: (a) 3D Schematic, (b) A-A Cross section

Subsequently, the system dynamic equations are derived and solved to estimate the resulting output power and the behavior of the transducer.

4.1 - Electret Layer

The electret layer is a dielectric layer with quasi-permanent polarized charges that can last for years. It is used to produce charges on the movable electrode using charge. Such layer can be modeled using Gauss's law. The voltage across the electret layer is given by:

$$V_{electret} = \frac{Q}{C_e} + \sigma \frac{d}{\epsilon_0 \epsilon_e} \quad (1)$$

$$= \frac{Q}{C_e} + V_e$$

where σ is the surface charge density, d is the electret layer thickness and ϵ_e is the relative permittivity of the electret material. Therefore, the electret layer can be modeled as a series voltage source V_e and a fixed capacitor C_e .

4.2 - Capacitance Modeling

The two variable capacitors are implemented as slabbed parallel capacitors with in-plane variation. Such structure allows successive maxima and minima to occur in one vibration cycle. Moreover, increasing the number of fingers of the fixed electrode with respect to the movable electrode ensure the same value for the maxima and minima positions within the vibration cycle.

Assuming linear variation of the capacitance with the overlap area, the capacitance of the variable capacitors can be calculated using the formula:

$$C_i(x) = C_0 X_{f1} \left[1 + (-1)^{i+n} \left(\frac{2x - np}{p/2} \right) \right] + X_{f2} \quad (2)$$

$$\left(n - \frac{1}{2} \right) p/2 < |x| < \left(n + \frac{1}{2} \right) p/2$$

where $n = \dots, -2, -1, 0, 1, 2, \dots$ to account for different lateral displacement, $i = 1, 2$ to account for both variable capacitors, p is the finger pitch and C_0 is the initial capacitance of both variable capacitors and equal to:

$$C_0 = \epsilon_0 \frac{hw_{slab}L_y}{2g} \quad (3)$$

where h is the number of slabs in the movable electrode in each of the variable capacitors, w_{slab} is the slab width, L_y is the generator width and g is the gap between the movable and fixed electrode.

X_{f1} and X_{f2} are fitting parameters to account for the fringing field. Since the affect of fringing field is difficult to estimate analytically, finite element analysis is used to calculate the actual capacitance at different lateral positions at a fixed width to gap ratio ($w_{slab} = 10g$). Figure 3 shows the normalized capacitance for three cases: linear, finite element and modified linear relations with $X_{f1} = 0.8$ and $X_{f2} = 1$.

It is clear that fringing field should not be neglected and the fitting parameters allow scaling of the linear relation to reflect the fringing field effect. Note that the value of the fitting parameters depends on the width to gap ratio (w_{slab}/g) and the pitch to width ratio (p/w_{slab}).

4.3 - System Modeling

The dynamic model of the transducer consists of three dynamic variables q_1 , q_2 , and x , where q_1 , q_2 is the electric charges on the variable capacitors C_1 and C_2 respectively while x is the mechanical displacement of the movable electrode. Assuming the system vertical stiffness is much larger than its lateral stiffness, the system dynamic equations can be written as:

$$R \frac{dq_1}{dt} = -V_1(q_1, x) - \frac{q_1 + q_2}{C_e} + V_e$$

$$R \frac{dq_2}{dt} = -V_2(q_2, x) - \frac{q_1 + q_2}{C_e} + V_e \quad (4)$$

$$m \frac{d^2x}{dt} = F_2(q_2, x) - F_1(q_1, x) - kx - B \frac{dx}{dt} - ma(t)$$

where the 1st two equations is the kirchoff's voltage law governing the electrical behavior of the transducer while the third equation is the Newton's law of dynamics in which m , k , B and $a(t)$ are the mass of the mechanical resonator,

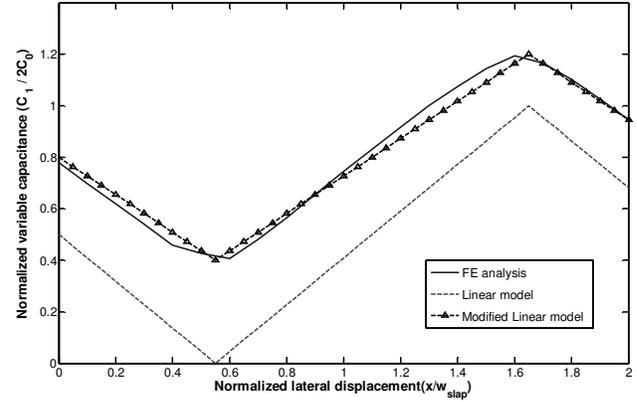


Figure 3 – Modified linear model in comparison of linear and finite element analysis for $w_{slab} = 10g$ and $p = 2.2w_{slab}$

mechanical lateral stiffness, the damping coefficient and the acceleration caused by the vibration source, respectively.

The resulting system equations after substituting for the voltages by ($V=q/C$) and the electrostatic forces by ($F=d(qV/2)/dx$) are non-linear differential equations that can not be solved analytically. Moreover, linearization of these system equations proved to be inaccurate when being used in optimization of the system parameters [5]. Therefore, numerical methods are used to solve the system differential equations using ODE solvers available in MATLAB. The total average output power is calculated by averaging the instantaneous output power $P(t)$ calculated using:

$$P(t) = \left(\left(\frac{dq_1}{dt} \right)^2 + \left(\frac{dq_2}{dt} \right)^2 \right) R \quad (5)$$

The average output power is used as an optimization goal using the same system parameters employed on the previous comb-finger implementation listed in Table 1 [5].

Table 1 – Summary of transducer used parameters.

Electret voltage (V_e)	150V	Damping Coefficient (B)	25.5 μ Ns/m
Transducer length (L_x)	5mm	Vibration acceleration (A)	163.8 m/s^2
Transducer width (L_y)	2.3mm	Vibration frequency (ω)	5724 rad/s^2

5 - SIMULATION RESULTS

The numerical solution of the systems differential equations using MATLAB and the optimization of the design parameter using the approach introduced in [5] shows an improvement in the output power by more than 78% compared to the original comb-finger structure where the output power was less than 50 μ W. The maximum average power is equal to 89 μ W and occurs at a load resistance equals to 6M Ω using

the same operating condition and sizes of the previously published implementation [5].

Figure 6 shows the resulting average output power at different natural frequency and load resistance. Note the flatness of the response for natural frequencies between 5600 rad/s and 5700 rad/s that results from limiting the lateral motion using a limiter for stable operation of the generator. Figure 4 presents the resulting lateral displacement of the shuttle and the normalized variable capacitors showing the occurrence of various maxima and minima in one vibration cycle. Figure 5 shows the charge on each of the variable capacitors normalized to the q_0 (stored charge when both capacitors are equal in capacitance). Table 2 summarizes the resulting dimension of the micro-generator transducer.

Table 2 – Summary of transducer dimensions.

Transducer Area	5mm x 2.3mm
Slab width (w_{slab})	40 μ m
Finger pitch (p)	88 μ m
No. of slabs	27
Electret area	2mm x 2.3mm
Gap between plates (g)	4 μ m

6 - CONCLUSION

A new planar electret based transducer implementation was introduced in this paper. The implementation was based on parallel plate topology. Modeling of different transducer component was presented taking into consideration the effect of fringing field. The resulting average output power of the optimized structure showed more than 78% improvement over the previous implementation. Such increase resulted from decoupling the period of vibration source from the electrical conversion cycle.

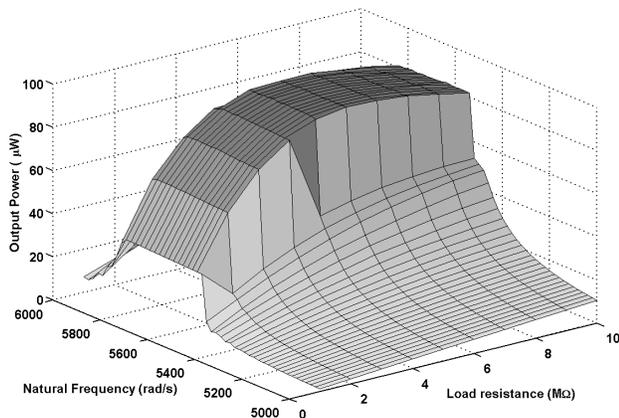


Figure 6 – Average output power for the proposed structure

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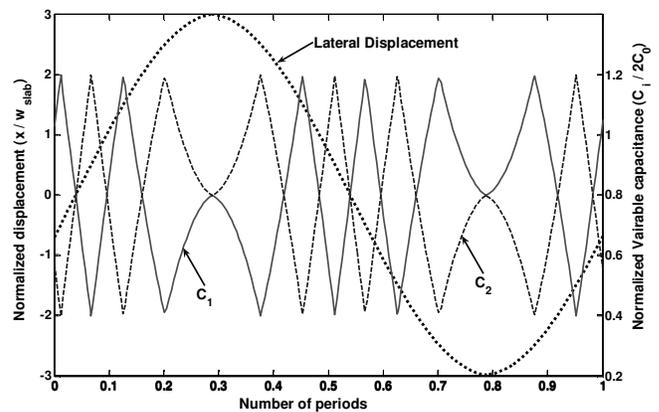


Figure 4 – Lateral displacement and variable capacitors in a complete vibration period

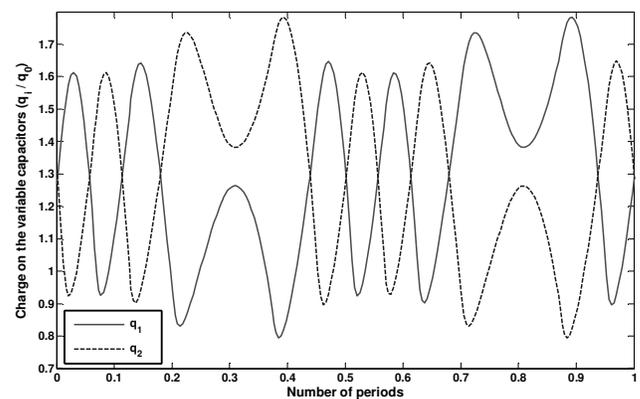


Figure 5 – Charge on the variable capacitors in a complete vibration period