DESIGN CONSIDERATIONS OF ELECTROSTATIC ELECTRODE ELEMENTS FOR IN-PLANE MICRO-GENERATORS

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Abstract: We present results from a theoretical design study of functional electrode elements for the design of electrostatic in-plane micro-generators. In this investigation we focus on the structural geometry of the variable capacitor elements and their impact on the device characteristics including total change of capacitance and dynamic stability. We found, that electrodes that combine sensitivity of both gap and area provide the greatest change of capacitance. However, electrostatic forces of electrode elements that comprise a gap-sensitive characteristic must be taken into account with respect to the voltage used to ensure the dynamic stability of electrostatic micro-generators. This paper presents a practical guide on how to design electrostatic dynamically stable micro-generators for specific operating conditions with a maximum of total capacitance change.

Keywords: Energy harvesting, Electrostatic, Micro-generator, Electrode Elements

1. INTRODUCTION

Energy Harvesting is an innovative technology that takes a vital key position when it comes to the implementation of self-sustaining systems. In recent years there have been great efforts in the development of energy harvesting devices for autonomous sensor and actuator systems [1].
One of the most challenging concepts for energy harvesting from vibrations is the employment of electrostatic micro-generators. This technology utilises a concept in which the conversion mechanism between kinetic and electrical energy is based on charge transportation between two variable capacitors. A major advantage of electrostatic micro-generators is their compatibility with CMOS fabrication technologies and small size, which makes them highly suitable for integration into sensor and actuator systems.

2. DESIGN

2.1 Device Concept

Design considerations for electrostatic electrode elements discussed in this paper are associated with a doubled variable capacitor concept as shown in Figure ***1***. This concept utilizes two variable capacitors with opposite capacitance-variations. For more details on the working principle of this device concept the reader is referred to the literature [2]. In order to compare different electrode elements, which build up the two variable capacitors, design considerations were based on a specific micro-generator layout.

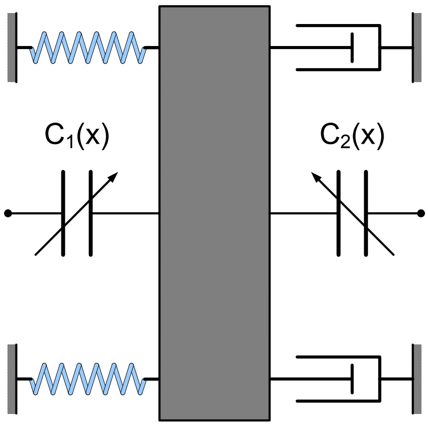

Figure 1: Device concept of the micro-generator

2.2 Micro-Generator Layout

The layout of the micro-generator is based on a fishbone structure, which comprises a seismic mass, a mechanical guidance and electrode structures (Figure 2). The mechanical guidance is realized by single-folded beam-elements, which allow the seismic mass to move with a inner displacement amplitude x_{max} of 20 µm. The electrode structures are placed into the vacancies between the fish bones (green areas in Figure 2) in such a manner that electrodes C_{1i} and electrodes

C_{2i} contribute to the total capacitance variation of the variable capacitor C_1 and C_2 respectively. The total usable length L_g, which the layout provides for housing electrode elements, is 13.6 mm.

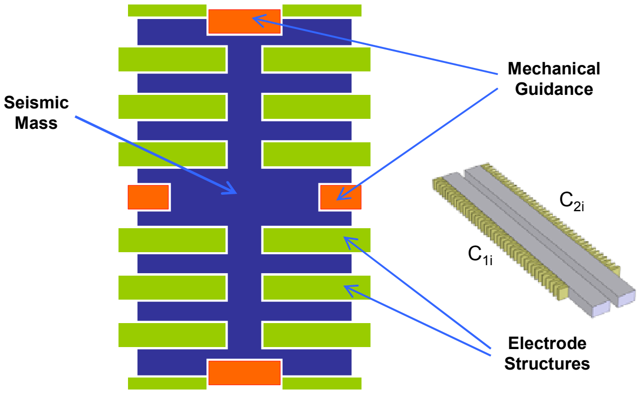

Figure 2: Layout of the micro-generator

2.3 Electrode Designs

In this investigation four different electrode geometries were analyzed. Well-known electrode geometries for electrostatic micro-generators are area-sensitive and gap-sensitive structures of interdigitated finger elements (Figure **3**a, b) [1-2]. A more advanced electrode geometry incorporates sensitivity of both area and gap by introducing a modified finger element with angled sidewalls as shown in Figure **3**c (EG3).

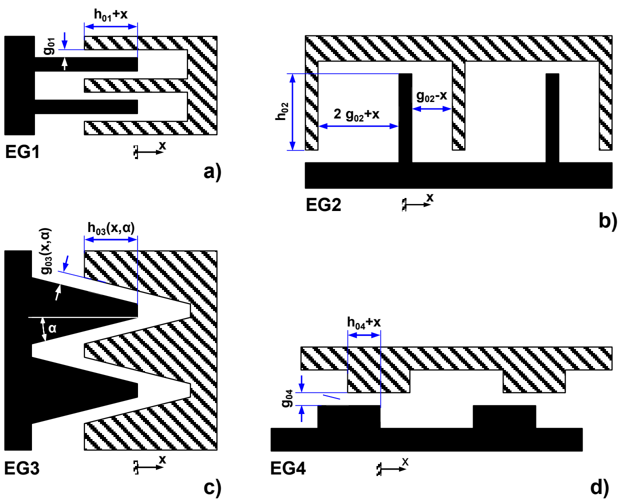

Figure 3: Electrode Designs; a) area-sensitive; b) gap-sensitive; c) angled; d) area-sensitive

A further geometry describes an area-sensitive electrode element EG4 where fingers do not interdigitate (Figure 3d) [3].

In general, electrostatic micro-generators require a substantial change of capacitance when oscillating in the range equal to the inner displacement amplitude. The total change of capacitance ΔC is very dependent on the number of electrode elements that can be incorporated into a particular design.

The number of electrode elements that can be arranged into the specified micro-generator layout is given for each of the four different electrode geometries by equation (1) to (4):

$$N_{EG1} = \frac{L_g - F_B}{2 \cdot (F_B + g_{01})} \approx 1038 \quad , \qquad (1)$$

$$N_{EG2} = \frac{L_g - F_B}{2 \cdot F_B + 3 \cdot (x_{max} + s_{02})} \approx 190 \quad , \qquad (2)$$

$$N_{EG3} = \frac{L_g - 4 \cdot F_B}{2 \cdot (\frac{s_{03}}{\sin(\alpha)} + 2 \cdot x_{max}) \cdot \tan(\alpha) + 2 \cdot F_B} \approx 520 \quad , \qquad (3)$$

$$N_{EG4} = \frac{L_g}{2 \cdot F_{B4}} \approx 164 \quad , \qquad (4)$$

where L_g is the total usable length, $F_B = 4$ µm is the finger width, $g_{01} = 2.5$ µm is the characteristic gap for EG1, $s_{02} = s_{03} = 0.5$ µm are the minimum gaps at x_{max} for EG2 and EG3, $\alpha = 11.6°$ is the angle of the sidewalls, $F_{B4} = x_{max}$ is the finger width for EG4 and $x_{max} = 20$ µm is the inner displacement amplitude.

To allow appropriate comparison between the different electrode designs, the minimum gaps s_{02} and s_{03} were chosen to be equal at the corresponding inner displacement amplitude x_{max} and $-x_{max}$ respectively. Also, the gaps g_{01} and g_{04} (see Figure **3**) were chosen to be as small as possible with respect to the technological limitations of our micro-fabrication facilities.

Electrode design EG1 allows with N_{EG1}=1038 the greatest number of electrode elements to be accommodated by the generator layout. This number is only dependent on the width of the fingers and the gap between them. For design EG3 the number N_{EG3} depends also on the angle α and the inner displacement amplitude x_{max}. Therefore, the smallest possible angle should be used, which is dependent on the smallest feature size that can be fabricated.

3. DISCUSSION

3.1 Capacity

The capacitance $C(x)$ and the total change of capacitance $\Delta C = C_{max} - C_{min}$ where $C_{max} = C(x_{max})$ and $C_{min} = C(-x_{max})$ are discussed. In this respect only C_1 is considered here since C_2 behaves complementary. The capacitance as a function of displacement for each electrode design is described by equation (5) to (8):

$$C_{EG1}(x) = 2 \cdot \varepsilon \cdot F_T \cdot \frac{(x_{max} + x)}{g_{01}} \quad , \qquad (5)$$

$$C_{EG2}(x) = \frac{\varepsilon \cdot h_{02} \cdot F_T \cdot 3 \cdot (x_{max} + s_{02})}{(x_{max} + s_{02} - x) \cdot (2 \cdot (x_{max} + s_{02}) + x)} \quad , \qquad (6)$$

$$C_{EG3}(x) = 2 \cdot \varepsilon \cdot F_T \cdot \left[\frac{x_{max} + x}{(s_{03} + (x_{max} - x) \cdot \sin(\alpha)) \cdot \cos(\alpha)} + \tan(\alpha) \right] , \qquad (7)$$

$$C_{EG4}(x) = \frac{\varepsilon \cdot F_T \cdot x}{g_{04}} \quad , \qquad (8)$$

where ε is the permittivity, $F_T = 50$ µm is the height of the electrode elements, $h_{02} = 40$ µm is the overlap for EG2 and $g_{04} = 2.5$ µm is the characteristic gap for EG4.

In Figure ***4*** the capacitance as a function of displacement is shown, taking into account the number of elements that the specified micro-generator layout is able to accommodate. Geometry EG3 produces the greatest change in capacitance followed by geometry EG1 and EG3. For the design of an electrostatic micro-generator EG1 and EG3 are to seen to be most favorable. However, other criteria such as stability must also be considered when designing an electrostatic micro-generator.

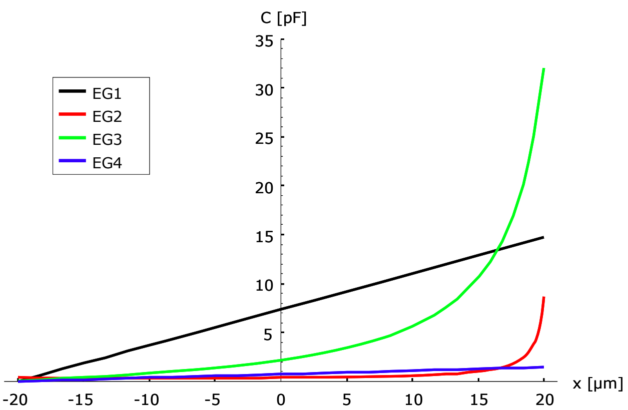

Figure 4: Capacitance versus displacement

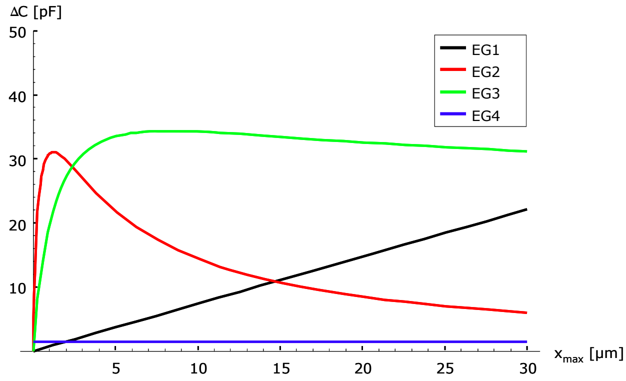

Figure 5: Total change of capacitance versus inner displacement amplitude

Figure 5 shows the total change of capacitance as a function of the inner displacement amplitude. In general, if x_{max} is not a definite constraint then it can be used as a variable design parameter to maximize the total change of capacitance. Electrode geometry EG3 is suitable for a wide range of inner displacement amplitudes larger than 4 µm since ΔC declines only very slowly. However, when designing electrostatic micro-generators with $x_{max} < 4$ µm electrode design EG2 is more applicable. Electrode geometry EG1 should be implemented for $x_{max} > 15$ µm.

3.2 Dynamic Stability

For electrode elements that comprise a gap-sensitive characteristic, dynamic stability is an important design issue with regard to the mechanical spring constant and the voltage across the electrode elements. Electrostatic forces increase dramatically when the inner displacement of the seismic mass approaches the maximum displacement x_{max} since the capacitance gradient rises in the same manner (see equation (9)). In order to analyze the stability accurately both capacitors C_1 and C_2 must be considered. The total electrostatic force follows from equation (10).

$$F_{C_j}(x) = \frac{1}{2} \cdot U^2 \cdot \frac{\partial C_j(x)}{\partial x} \quad . \qquad (9)$$

$$F_{el}(x) = F_{C_1} + F_{C_2} \quad . \qquad (10)$$

Figure ***6*** shows the total electrostatic force for each electrode design and the spring force. The voltage across the electrodes is 50 V whereas the

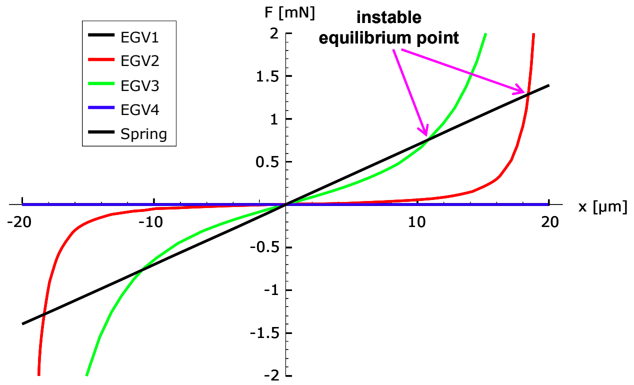

Figure 6: Electrostatic and spring force

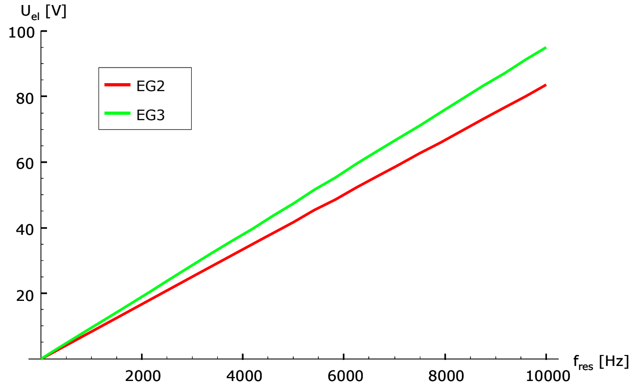

Figure 7: Voltage versus resonance frequency

spring constant was designed to obtain a mechanical resonance frequency of 1650 Hz. In this particular case the repulsive spring force and the resulting electrostatic force reach equilibrium for a displacement smaller than x_{max}. Consequently, the micro-generator becomes instable and will not operate properly. In this case, if the inner displacement exceeds the point of equilibrium, the seismic mass will be driven towards the limit stop remaining in this position. Therefore, the operational parameter voltage requires to be accounted for when designing electrostatic micro-generators for a specific frequency using electrodes with a gap-sensitive characteristic (i.e. EG2 and EG3).

In order to achieve a stable system, the instable equilibrium point must be located beyond x_{max}. Consequently, the voltage used to operate the electrostatic micro-generator must be adjusted with regard to the spring constant and hence to the operational resonance frequency. The relationship between voltage and eigen angular frequency is shown in Figure *7*. This graph can be seen as an approximate design rule when using electrode designs EG2 or EG3. For low frequency applications (< 2000 Hz) the voltage that can be applied (i.e. by an electret) falls below 20 V. In this respect it must be noted that the characteristic angular frequency of the generator system will shift towards lower frequencies due to the spring-softening effect, which is caused by the attractive electrostatic forces. Therefore, the mechanical spring must be designed in accordance with the voltage across the electrode elements in order to counteract the softening effect.

4. CONCLUSION

In this paper different electrode geometries for electrostatic micro-generators were investigated. A modified geometry was introduced to provide a greater change of capacitance within an oscillating period. When using electrode designs with a gap-sensitive characteristic, the stability of the system must be considered. In this respect the location of the instable equilibrium point must lie beyond the inner displacement amplitude, which limits the applicable voltage for a specific frequency. For low frequency applications electrodes EG1 should be used while EG3 can be employed for frequencies in the kHz range.

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