Simulation of Electrostatic Actuation in Interdigitated Comb Drive MEMS Resonator for Energy Harvester Applications

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Abstract. This paper presents an actuation mechanism based on the interdigitated comb drive MEMS resonator. The important role of that device is to establish MEMS resonators for the second order systems. Comb drive model is one of the basic model which uses the principle of electrostatic and force can be generated for the capacitive sensors. This work is done by overlapping movable and fixed comb fingers which produces an energy. The specific range of the polyimide material properties of young’s modulus of 3.1GPa and density of 1300 Kg/m³. Results are shown in the structural domain performance of a lateral motion which corresponds to the applying voltage between the interdigitated comb fingers. It has laterally driven about 40μm with driving voltage. Also the resonance frequency 24Hz and 15Hz with high quality factors are depending on the spring length 260μm and 360μm and structure thickness of 2μm and 5μm. Here Finite element method (FEM) is used to simulate the various physics scenario and it is designed as two dimensional structure multiphysics domain. The prototype of comb drive MEMS resonator has been suitable for energy harvesting system applications.

Keywords: MEMS resonator, Interdigitated combs, Electrostatic actuation, FEM and Energy harvester

1. Introduction

The innovation of interdigitated electrode resonator has been development in various devices or systems like as gyroscope, frequency references, filters, and microtweezers [1-5]. Generally the resonator structure is one of the most fundamental model for key research in MEMS resonators. The electrostatic displacement and deformation are some of the driving mechanisms utilized in comb drive MEMS resonator. The three dimensional comb drive resonators are used to develop the MEMS based device or systems, which can bring significant benefits from sensing to energy harvester applications. Generally these systems include movable and fixed electrode excited which are led by DC and AC voltages on one or both sides [6-9]. The comb drive MEMS resonator is laterally driven by micromechanical actuator due to an electrostatic force [10, 14]. Since, the interdigitated combs like as capacitive sensors, it is often used as a linear resonators that utilise the electrostatic forces between the overlapped combs at the micro or nanometre scale. The goal of electrostatic force has inversely proportional to the square of the overlapping combs between the gap distance of the interdigitated comb

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drive (IDC) MEMS resonator. The device has been designed on a three-dimensional structural form to compute the finite element analysis (FEM). The electric potential and deformation of the comb drive [6], electrostatic force and structural problems of levitation [10], quadratic shaped combs of cubic electrostatic [12], the butterfly-shaped stiffness are studied in FEM [13]. Energy harvesting systems are used to capture the energy naturally from the environment such as vibration [9,15]. In this paper, we use the finite element analysis to obtain accurate results.

2. Design of Interdigitated comb drive:

IDC MEMS devices are extensively used in capacitance-based actuators. A prototype is designed with a rectangular-shaped comb drive consisting of interdigitated comb drive design a one fixed and the other connected to a flexural folded beam. When voltage is applied to structure between the overlapping combs, a displacement of movable combs towards the fixed comb generates an electrostatic force in the direction opposite to the direction along the length of the combs. Electrostatic force is generated along the overlapping comb fingers and it produces a capacitance, therefore the total capacitance is the sum of capacitance contributed by neighboring comb fingers. The opposite walls of comb fingers in the overlapping region form a parallel plate capacitor contributing a capacitance $C$. Let $C_1$, $C_2$ be the capacitances between the cavity of fixed comb fingers and the movable comb fingers attached with the shuttle mass along the x-axis and y-axis, respectively. The analytical estimation of fringe capacitance $C_2$ is difficult. However, the accurate way to estimate for the fringe capacitance is by Finite Element Method (FEM), so far the fringe field capacitance should be ignored.

The structural designs of polyimide material based MEMS resonators are shown in Fig.1 and important geometry dimension shown in table 1.

![Fig.1. Schematic structure of IDC MEMS resonator](image)

Here, the capacitance between the movable combs and fixed combs on either side can be determined as

$$C(x) = \frac{2N\varepsilon_0(y_0 + y)}{T_{th}}$$

(1)

where, $N$ is the total number of movable comb fingers, $y_0$ is overlap comb finger, $y$ is displacement in y direction, $T_{th}$ is thickness of the structure layout and $g$ is gap between the fixed and movable comb fingers on the one side.

Electrostatic force is obtained from the comb drive can be expressed as
\[ F(x) = \frac{1}{2} \frac{\partial^2 C(x)}{\partial x^2} V^2 \]

where, \( V \) is the excitation voltage. Thereafter, taking the derivative of \( C(x) \) with respect to \( x \) and the electrostatic force is simply driven on comb drive resonator as expressed by [5]

\[ F = \frac{N_{e0} T_{th} V^2}{g} \]

(2)

The capacitance \( C \) is generated between overlapping comb fingers can be store the energy \( U \) is obtained as following as [18]

\[ U = \frac{1}{2} CV^2 \]

(3)

Table 1. Important dimension of the interdigitated comb drive MEMS Resonator

| S.No | Part description | Designed Value |
|------|------------------|----------------|
| 1    | Structure thickness \( T_{th} \) | 2 \( \mu \)m, 5 \( \mu \)m |
| 2    | Different number of movable combs | 5, 7, 9 |
| 3    | Mass width \( W_m \) | 20 \( \mu \)m |
| 4    | Mass length \( L_m \) | 75 \( \mu \)m |
| 5    | Gap \( g \) | 5 \( \mu \)m, 10 \( \mu \)m |
| 6    | Comb finger width \( W_{comb} \) | 7 \( \mu \)m |
| 7    | Comb finger length \( L_{comb} \) | 80 \( \mu \)m |
| 8    | Overlapping combs \( y_0 \) | 40 \( \mu \)m |
| 9    | Flexural folded beam spring length \( L_s \) | 360 \( \mu \)m & 260 \( \mu \)m |
| 10   | Flexural folded beam spring width | 5 \( \mu \)m |
| 11   | Anchor size width \( \times \) length | 35 \( \mu \)m \( \times \)35 \( \mu \)m |
| 12   | Truss width | 35 \( \mu \)m |
| 13   | Truss length | 100 \( \mu \)m |

3. Dynamics of Mechanical Resonator:

The dynamics of the laterally driven comb-drive is single degree of freedom from second order system. Since, the mass damper and stiffness involved in the actuation mechanisms. The IDC MEMS resonator consists of mass connected to a flexural folded beam that itself is anchored to the comb drive as shown in Fig. 1. When acceleration is applied to the mass, a displacement is sensed using capacitive comb drive which is attached to the mass. Therefore, the mass can be expressed as

\[ M = A \rho T_{th} \]

(4)

where ‘A’ is the total area obtained from the structure, ‘\( T_{th} \)’ is the structural thickness and \( \rho \) is the density of Polyimide (1300 kg/m²). The mass value \( M \) (\( M = 3.90 \times 10^{-6} \) Kg, \( M = 9.75 \times 10^{-6} \) Kg) is calculated for thickness 2\( \mu \)m and 5\( \mu \)m.

Another important parameter is folded beam selection, it exhibits a large linear displacement and it have a high lateral stiffness ratio, to reduce cross-axis sensitivity.

The key objective of the paper is to study the fixed guided beam selection by considering one as a straight cantilever beam, since the beam satisfies Euler-Bernoulli beam theory and the linear spring constant in \( x \)-direction. The stiffness due to load at the tip of the beam is derived as

\[ K = \frac{E T_{th} W_s^3}{L_s^2} \]

(5)

where, \( K \) is spring constant, \( E \) is Young’s modulus of the Polyimide material 3.1GPa, \( T_{th} \) is structure thickness, \( W_s \) is folded spring width, and \( L_s \) is folded spring length.

The resonance frequency formula is written as
\[ f_r = \frac{1}{2\pi} \sqrt{\frac{K}{M}} \]  \hspace{1cm} (6)

where, \( K \) is stiffness constant and \( M \) is mass of the comb drive device.

A prediction of the quality factor is significant as it influences the mechanical noise of the resonator. The important parameters a quality factor \( Q \) is derived using the equation (7)

\[ Q = \frac{K}{f_r C_{Total}} \]  \hspace{1cm} (7)

where, \( C_{Total} \) the total damping coefficient, and \( f_r \) is resonance frequency. Since, the estimated air damping effects are approximated by two mechanism known as slide film and squeeze film damping. Above equation is used in deriving the results of resonance frequency in 24Hz with high quality factor \( Q=2712432 \) for beam length 260\( \mu \)m and 15Hz with quality factor \( Q = 16799232 \) obtained for 360\( \mu \)m beam length in thickness 5 \( \mu \)m.

4. Analysis of Finite Element Methods:

The COMSOL Multiphysics is a software that adequate to both creating and modelling of the physical scenarios. The numerical solutions are obtained through finite element method (FEM) simulation in COMSOL Multiphysics 4.4 [6,12,16]. This technique approximates the solution to partial differential equations by taking a model and separating it into a number of discrete smaller geometric entities. By solving the complex problem in MEMS area the free triangular meshing is done for 3D rectangle comb drive geometries compute FEM analysis in an accurate manner. This simulations of electrostatic actuation were performed for various mesh densities for the quadratic and linear elements [9]. However, the density selection of the typical values are available in COMSOL Multiphysics and it is varied from the extremely coarse to extremely fine densities. Here, fig 2 shows the triangle mesh with fine densities.

Fig 2. Triangular Mesh (Fine)

In this paper, FEM techniques has delivered the accurate solution and potential distributions. The electric potential has a continual quantity of the electric energy, the basic requirement for finite element method is derived by the system. This kind of simulation has analysed the stiffness of flexural beam and static displacement of the parametric resonators.

5. Results and Discussion:
The simulation design of comb drive MEMS resonators on the geometries, materials, mesh, voltages, stress, electrostatic potential and displacements are studied and analyzed.

5.1 Analysis of Electrostatic Actuation and Displacements:

This research work is carried out for different number of comb fingers (5,7,9) number flexural folded beam length (260µm and 360µm) and different gap (5µm and 10µm) between the interdigitated combs. First, the design is involved with pre-processor steps that involved geometries in micro level, and the structure design using the parameters shown in table 1. Polyimide material can applied to 3D model and surrounded by an air medium. However the solid structural mechanism offers the mesh settings and boundary condition [6]. Here, the IDC MEMS resonator has taken for 260µm folded beam length, the gap between overlapping combs for 5µm are shown in illustration 3(a) to (f) for 5, 7 and 9 number of comb fingers respectively. In order to study the characteristics of the IDC MEMS resonator the electric potential have been varying 0V to 5V voltage.

When 5V voltage is applied to the model, the electrostatic force produced in horizontal surface on the x direction, and the energy is stored between the overlapping combs like as capacitors are shown in fig 3.(a),(c) and (e). This resonator model were parametrically excited with the resonance frequency. The mechanical actuation of the models are show in fig 3.(b),(d) and (f). The soft-hard spring can exhibited for IDC MEMS resonators structure. Electrical and mechanical interaction of the MEMS resonator for the linear displacements are depicted.

(a) Combs 5, g=5µm & l=260 µm
(b) Combs 5, g=5 µm & l=260 µm
(c) Combs 7, g=5 µm & l=260 µm
(d) Combs 7, g=5 µm & l=260 µm
Fig. 3. (a), (c) and (e) Electric Potential 5V  
(b), (d) and (f) Total Displacement 5V

Fig. 4. Applied voltage vs. electrostatic forces

Fig. 4 shows the applied voltage versus electrostatic force graph. In this case of IDC MEMS resonator structure for a gap of 5µm and 10µm, the thickness of the structure is considered 2µm and 5µm respectively. When voltage is applied to comb drive model an electrostatic force is produced linearly [6]. The electric potential energy is gradually increased by voltages, thus comparison result of the resonator gets high electrostatic force for the structure of gap 5µm and thickness 5µm.

5.2. Resonance Characteristics:

In order to design the beam length of 260µm, gap 5µm and thickness 5µm of the structure layout of resonance frequency was obtained from equation (6) the $f_r = 24$Hz with a quality factor $Q = 10117632$ shown in fig. 5.(a). There after the resonance frequency $f_r = 15$Hz with $Q = 6799232$ found for resonator structure beam length 360µm at the same gap and thickness are shown in illustration 5.(b). In which the comb drive MEMS resonator was tunable resonance frequencies from 15Hz to 24Hz respectively. The comb drive resonator cannot maintain the high amplitude as a consequence of this, the resonator gets an unstable and begins to vibrate at lower amplitude in order to sustain the oscillations [6, 9, 11, 16]. While comparing the results it is found that, when the structure length is decreased the resonance frequency is increased and vice versa.
Fig. 5. (a). Frequency vs. amplitude at beam length of 260\(\mu\)m
(b). Frequency vs. amplitude at beam length of 360\(\mu\)m

5.3. Capacitance

Fig. 6. (a) and (b) Capacitance vs. displacement with beam length of 260\(\mu\)m

Fig. 7. (a) and (b) Capacitance vs. displacement at beam length of 360\(\mu\)m
The above illustration 6 and 7 show that displacement versus the capacitance of the three different number of combs. The good results are obtained from equation (1) for the electrostatic overlapping combs finger that creates the capacitance in the range of femoto level. For the micro level mechanical structure comb finger is inversely proportional to gap distance. Here, firing field capacitance can be ignored and overlap comb distance was calculated.

The solution showed that the 5µm gap between overlapping combs and 9 combs give high capacitance. In order to increase the gap displacement in x direction, the capacitance are tend to saturate. Energy harvester system is generated to approximate the electrostatic force between the fixed combs and movable combs structures in the x and y directions [9,19]. This energy is increased and capacitance halved, the charge from the overlapping comb fingers like as two parallel plate capacitors [17]. The coupling system depicts on the capacitive transducer mechanism like as energy storage system [20,21].

1 2 3 4 5

(a) l=260µm, g=5µm & 10µm
(b) l=360µm, g=5µm & 10µm

Fig.8. (a) and (b) Voltage vs displacement

Fig.8 (a) and (b) graph represent the relationship between the applied voltage and displacement of the 3 different combs 5,7,9. The displacement increases gradually with the increase of the voltage. Here, the results show the beam length 360µm with 9 combs and gap 5µm is better displacement than all other parameters. This actuation mechanism is based on the electrostatic actuation in IDC MEMS resonator [18].

This IDC MEMS resonator is mainly the principle based an electrostatic actuation. These electrostatic actuator are driven on horizontal surface in x direction for producing an electrostatic forces and store some energy [16]. The goal of finite element method was accurate for the electric potential distribution and deformation analysis.

The application part of this electrostatic IDC MEMS resonator is used an energy harvester system based on capacitance with displacement and also the resonance frequency. The performance are analysed for the specific parameters of the IDC MEMS resonator in multiphysics domain. In addition the soft spring and hard spring effect exhibited in parametrically resonator [6,18]. The post- processing of the graphs are plotted as capacitance vs. displacement, frequency vs. amplitude and voltage vs. electrostatic force. The resonance frequencies with Q factor was reported for the various dimensions. The IDC MEMS resonator device is exhibited a good results in resonance frequency range of 24Hz with quality factor 10117632, capacitance 27704fF for the 9 movable comb fingers, spring length 260µm and thickness 5µm. So far the device is well known for the vibration to energy harvesting applications.

CONCLUSION

This paper presents the simulation design and modelling of interdigitated comb drive MEMS resonator for energy harvester. The vibrating energy of the mechanical resonator for parametrically excited resonant frequency are studied. The solution compares the folded beam, gap, different number of combs 5,7,9 are depicted. This geometries are done by three dimensional design using COMSOL.
multiphysics 4.4 software. This shows good results on the length of beam 260µm, gap 5µm and 9 movable combs are obtained from the capacitance 27704fF. Thereafter the resonance frequency is tuneable for 15Hz to 24Hz and the device quality factor is also presented. The role of research work on FEM model offers accurate analysis using multiphysics domain and linear displacement. IDC MEMS resonator has been suitable for energy harvesting system applications.

Nomenclature

- MEMS: Micro Electro-Mechanical Systems
- IDC: Interdigitated Comb Drive
- FEM: Finite Element Methods
- C: Capacitance
- E: Young’s modulus of the material
- K: Spring constant
- M: Mass
- N: Number of comb fingers
- Q: Quality factor
- ρ: Density of materials
- Ctotal: Total damping coefficient
- fr: Resonance frequency
- Tth: Thickness of structure

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