A Novel Capacitance Control Design of Tunable Capacitor Using Multiple Electrostatic Driving Electrodes

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Abstract

A novel control design method that is capable of linearly electrostatic driving a tunable capacitor is proposed in this paper. By extending the derivation of electrostatic theory and elastic theory in constructing the tunable capacitor, the nonlinear relationship between applied voltages and displacement (air gap) between two parallel plates of the capacitor is obtained. To suppress the nonlinearity so that the gap between the capacitor can vary linearly with the applied voltage, a control design method based on the variation of the multi-rectangular electrodes and applied voltages is proposed. By varying the number of rectangular electrodes that are evenly divided according to the size of the upper plate of the capacitor, the working space of the tunable capacitor with nonlinear characteristics is obtained. With this working space, linear control design method based on fixed or linearly varied applied voltages can be used to determine the number of the multi-rectangular electrodes such that stepping effect of the tunable capacitor can be achieved. Examples are used to demonstrate the feasibility of the present control design. Simulation results indicated that the linear control design method matched closely with the analytical analysis.

1. Introduction

Micro-electro-mechanical System (MEMS) devices are being widely used for various microwave and millimeter wave applications in the last decade. One of the most important components used in VCO circuits of RF systems is the tunable capacitor [1][2]. For MEMS based capacitors, mechanical tuning avoids high losses associated with semiconductors at high frequencies. Furthermore, the use of air gap instead of other dielectric materials makes high-Q capacitors possible [3][4].

Among the purposed MEMS designs, the capacitor's tuning range and its transfer characteristic are the most important indices for the performance measurement of the tunable capacitor. Several electro-statically and thermally actuated designs [2-5] had been demonstrated in the past for the improvement of the capacitor's tuning range. However, the non-linear transfer characteristic existed in these designs limits the feasibility of practical realization.

In order to overcome this drawback, a novel control design for electrostatic actuated MEMS based tunable capacitor is purposed. Firstly, by utilizing the elastic and electrostatic principles of the upper plate that also possesses suspending beams, the relation between applied voltage and displacement of the tunable capacitor is known. Secondly, by varying the number of pre-designed rectangular electrodes that are evenly divided according to the upper plate size of the tunable capacitor, the working space with respect to the applied

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voltage and the location and the size of the individual electrodes is obtained. Thirdly, linear control designs based on fixed or linearly varied applied voltages are used to determine the number of the multi-rectangular electrodes such that stepping effect of the tunable capacitor can be achieved. Finally, numerical examples are given to demonstrate the feasibility of the present control design by comparing the results with existing simulation software.

2. Principle of Control Design

Figure 1 shows the typical electro- statically actuated tunable capacitor model for improving the tuning range [5]. The variable capacitance C, which is formed by suspended plate E_1 and fixed plate E_3, can be tuned by electrostatic force generated by voltage drop between E_1 and E_2 plates.

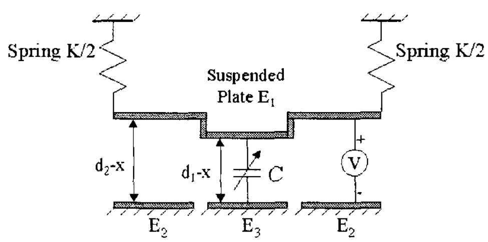


Fig 1 Conceptual model of the tunable capacitor

By dividing the original driving electrode on the bottom plate into multiple electrodes that are illustrated in Figure 2, the system equation is given as follows:

$$kx = \sum_j \frac{1}{2}\varepsilon_0 V_{12}^2 \frac{A_{E2j}}{(d_2 - x)^2} \quad (1)$$

$$c = \varepsilon_0 \frac{A_{E3}}{(d_1 - x)} \quad (2)$$

where k is spring constant, ε_0 is permittivity of air, V is applied voltage between electrodes , d is initial gap of electrodes, A is overlap area of electrodes, and x is the displacement of suspend plate E_1, and j=0,1, … … N, is the number of electrodes E_{2j}.

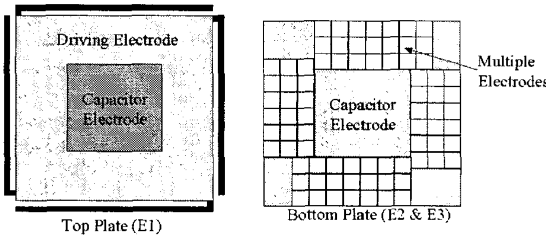


Fig. 2 The configuration of the tunable capacitor with multiple electrodes

Furthermore, if we consider the areas of the multiple electrodes on E_2 are equally divided, then equation (1) becomes

$$kx = M\frac{1}{2}\varepsilon_0 V_{12}^2 \frac{A_{E2j}}{(d_2 - x)^2} \quad (3)$$

where M is the total number of multiple electrodes we can utilize to apply control voltage. By varying the total number of multiple electrodes for the designed capacitor, the working space between the capacitance and applied voltage is varied accordingly. Table 1 lists the transfer characteristics of capacitor from single electrode to multiple electrodes. Clearly, we observe that the relationship between the applied voltage and capacitance is extended from a single nonlinear curve to a series of nonlinear curves. With these characteristics, control designs based on multiple rectangular electrodes that are evenly divided according to the size of upper plate E_1 is proposed. By linearly varying the air gap, the corresponding applied voltages and the number of multi-electrodes, M, can be obtained. Thus, by switching the designed electrodes adaptively, the capacitor would generate the desired multiple-stage capacitances.

Here, we define this region as the controllable working-space R_C. Within this working space, the transfer characteristic of the capacitor could be designed and fabricated according to desired applications.

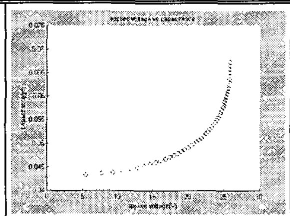
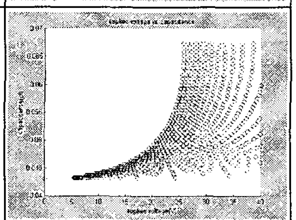
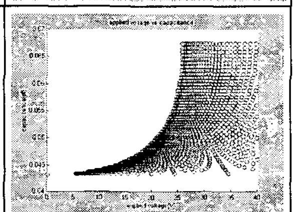
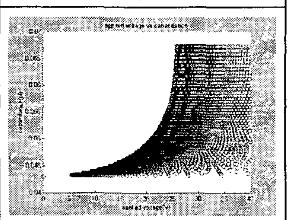
Number of Electrode	Capacitance vs. Applied Voltage
4(400um*100um each)	
80(40um*50um each) (20 each region)	
160(20um*50um each) (40 each region)	
320(20um*25um each) (80 each region)	

Table 1 Characteristics of capacitor with multiple electrodes

3. Control Design Using Multiple Electrodes

As described previously, the working space R_C determines the solution for the different combination of electrodes and applied voltage. Note that if a specific curve that represents a multi-stage displacement is needed for the design of a specific system, the possible solutions of applied voltage and the combination of multiple rectangular electrodes could be found in R_C.

By considering the example given in table 1 with 160 electrodes, Figure 3 show three control design methods, namely linear-, digital-, and hybrid-design, are proposed to demonstrate the proposed control design.

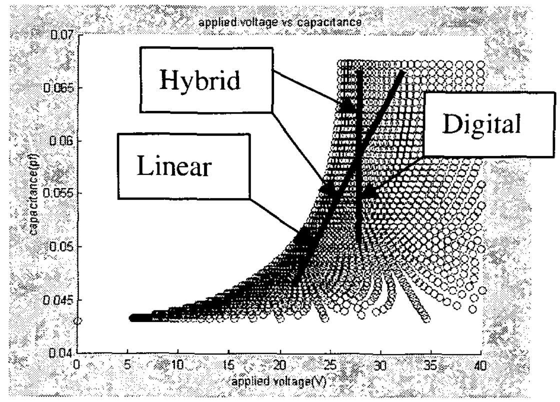


Fig 3 Working space and control design curves

After transferring the capacitance to displacement characteristics from equation (2), the electrode selection algorithm based on the minimization of error function, E, is applied to search for respective combinations of the number of electrodes that is given by:

$$E = \left| M \frac{1}{2} \varepsilon_0 V_{12}^2 \frac{A_{E2j}}{(d_2 - x)^2} - kx \right| \qquad (4)$$

where M=4, 8, 12, ... Table 2 lists the search results for three different cases.

Furthermore, by considering the practical applications such as VCO where the accuracy of the capacitance is the most important issue for the tunable capacitance. An optimal control method based on the Modified Genetic Algorithms (MGAs) [6] is adopted with given fixed capacitance and finite resolution of the supply voltage (e.g. 0.1 voltage for the present study). Table 3 lists the initial parameters of MGAs and Figure 4 shows two convergent optimal solution using MGAs.

Desired Capacitance	Designed Voltage	Number of Electrode	Calculated Capacitance	Error
0.051 pF (linear)	23V	144	0.05098 pF	0.039%
0.061 pF (linear)	28V	132	0.06025 pF	1.23%
0.065 pF (digital)	28V	136	0.06421 pF	1.22%

Table 2 Performance of multiple electrodes

Bits of chromosome	16
Number of population	50
Number of generation	100
Hybrid GA's operator	Yes
Heuristic fitness function	Yes
Immigrant operating factor	Yes
Self-adjustment parameter	Yes
Crossover rate	90%
Mutation rate	3%

Table 3 Initial parameters for MGAs

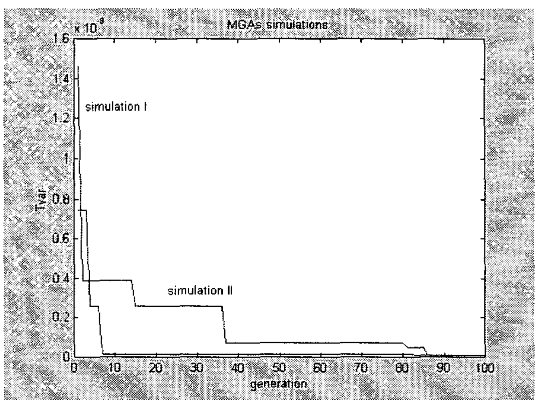


Fig 4 Simulation results using MGAs

4. Simulations Using Existing Software

In order to demonstrate the accuracy of the proposed control design, a commercial simulation tool for micro-electro-mechanical system design, IntelliSuite™ software, is used to verify the results obtained previously. By constructing the designed electrostatic tunable capacitor system, giving material properties and design parameters (shown in Table 4) and applying calculated voltage from the theory, simulation result of the displacement of the tunable capacitor is obtained and shown in Figure 5. With this result, the capacitance between two parallel plates can be calculated. Table 5 compares the FEM simulations using IntelliSuite™ and derived analytical results for three special cases.

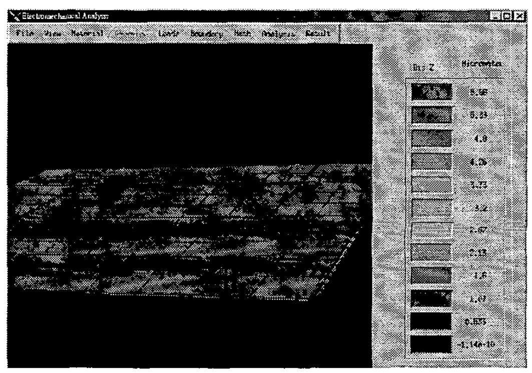


Fig 5 Simulation result of the displacement of the tunable capacitor

Material Parameters	Value
Young's Modulus	169Gpa
Poisson ratio	0.42
Permittivity	$8.854*10^{-12}$F/m
Beam Width, Thickness	2um
Beam Length	300um
Initial Gap(d_1,d_2)	18.5um, 20um
A_{E3}	$300x300um^2$

Table 4 Simulation Parameters

Desired Capacitance	Applied Voltage (designed)	Applied Voltage (calculated)	Number of Electrode	Capacitance FEM Simulation & error (comp. to design)	Capacitance FEM Simulation & error (comp. to theory)
0.063 pF	29	28.7763	128	C=0.0622 error=1.27%	C=0.0608 error=3.49%
0.059 pF	28	28.1955	128	C=0.0576 error=2.37%	C=0.0583 error=1.19%
0.065 pF	30	29.8482	120	C=0.063 error=3.02%	C=0.062 error=4.62%

Table 5 Comparisons between designed and IntelliSuite™ simulation results

Applied V	28 v			
Desired Capacitance	0.056 pF			
N	1	80	160	320
V_{ideal}		28.2265	28.2265	27.99418
M	Depend on applied	60	120	244
Capacitance(pF)	voltage	0.05544	0.05544	0.05602
Accuracy		1%	1%	0.036%

Table 6 Performance of the proposed control design (the number of driving electrodes is increased from 1 to 320)

Note that the error percentage of accuracy is below 5% and resolution is reaching 0.002pf for 160 electrodes case. Finally, in order to improve the accuracy and the resolution of the tunable capacitor, we can further divide the electrodes into smaller ones. As shown in table 6, while the number of driving electrodes is increased from 1 to 320, the variance of the accuracy between desired and actual capacitance is decreased from 1% to 0.036%

5. Conclusion

A novel capacitance control design of tunable capacitor using multiple electro- static driving electrodes had been proposed in this paper. Preliminary results have been verified through FEM simulations. With the proposed method, the tunable capacitor device can possesses different characteristics such as linear-, digital-, or hybrid-design. Furthermore, the variance of capacitance can be controlled accurately with specific resolutions. In our current research, the proposed MEMS based tunable capacitor is in the process of fabrication. Experimental results will be reported in the near future.

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