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Modelling of a Charge Control Method for Capacitive MEMS

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Abstract—Charging of dielectric materials in microelectromechanical systems (MEMS) is a major reliability issue. In our previous work we proposed a feedback control loop method that is implemented as a circuit and that allows smart actuation for switches and varactors. In this paper we discuss system-level modeling of MEMS devices including all aspects of the system: proposed control method, charging dynamics and realistic models of the mechanical components of MEMS.

I. INTRODUCTION

A variety of microelectromechanical systems including oscillators, variable capacitors (varactors) and switches are actuated electrostatically. Despite a number of advantages, this actuation technique may lead to the accumulation of charge in dielectric materials used for the fabrication of these MEMS. This is known to be a major reliability problem for these devices since the charge trapped in the dielectric causes a shift of the CV characteristic and permanent stiction of movable mechanical parts to actuation electrodes. This is especially a problem for radio frequency (RF) MEMS [1]. As is reported in recent reviews [2], [3], the accumulation of charge by dielectrics is very common and all typical dielectric materials are prone to it. In recent years an alternative approach that consists of bipolar [4] and smart actuation techniques [5], [6] is suggested to address the problem of dielectric charging.

In ref. [6] we proposed a smart actuation method that is based on a feedback control. We have investigated this method for a simple 1D model suitable for MEMS positioners and varactors which operate below pull-in of the MEMS structure. (Pull-in is a phenomenon when a movable suspended electrode collapses onto the fixed electrode since the electrostatic force can no longer be compensated by the restoring mechanical force). In addition, we experimentally demonstrated that the method can be applied to switches which operate beyond pull-in. However the simplest model investigated in that paper does not include certain effects that can be found in realistic mechanical structures. It also does not allow us to apply the theory and numerical simulation technique to switches. The aim of this paper is to present a system level model that includes all aspects of the system: the charge control method which is implemented in a circuit, a realistic model of the mechanical part of the device and the dynamics of dielectric charging/discharging with time. The main advantage of the improved model that it allows simulations both below and beyond pull-in, i.e. it is suitable for modeling of varactors, positioners and switches. In addition, it is rather simple and has a form of a nonlinear discrete-time mapping. We also discuss how to extract the data of the dielectric charge from experiment and apply this model to simulate realistic devices used in experiment in [6].

II. STATEMENT OF THE PROBLEM

A. Control Method for Dielectric Charge

The control method of dielectric charge, as shown in fig. 1, is based on the measurement of the capacitance of the device. As the capacitance of the device is related indirectly to the amount of the dielectric charge accumulated, at each time instant $nT_s$, the control method decides what voltage to apply for the next step $(n+1)T_s$ based on the state of the system. If $Q_d$ is the accumulated dielectric charge, it causes the effective voltage be different from the actual applied voltage $V$: $V_{act} = V - V_{shift}$, where $V_{shift} = \frac{Q_d}{C_d}$

The general form of a discrete-time mapping that describes the control method from fig. 1 is given in [6] in the following form:

$$T(Q_d, b) = \left( \frac{1}{2} \left[ 1 + \text{sgn} \left( C_{th} - \frac{\Theta(P; Q_d, b)}{\Theta(P; Q_d, b)} \right) \right] \right)$$

where $T(Q_d, b)$ is an evolution operator which describes the charging dynamics, $Q_d$ is the dielectric charge, $b$ is a decision bit sequence (for more details see [6]). $\Theta(P; Q_d, b)$ is a function that expresses the evolution of the dielectric charge (see Sec. II-B) with $P$ being the parameters of the charging model, $C_{th}$ is a capacitance reference, $C_{th,0}$ is the initial capacitance of the device (when no voltage is applied), $\gamma = C_{th,0}/C_d$ with $C_d$ the capacitance of the dielectric and...
time. The dielectric charge accumulates and causes the change constant voltage (either $C$. Improved Fitting of Experimental Data to be determined from fitting of experiment data.

There are three most commonly used semi–empirical charging models that can be found in literature (see review given in [6]).

In order to extract the realistic dynamics of the system beyond the pull-in voltage. When the movable electrode collapses onto the bottom electrode, the capacitance of the devices in the 1D model is always equal to the capacitance of the dielectric $C_d$. In addition, this model is unable to fit experimental data that is an important step for the analysis of the charging/discharging dynamics. Therefore, a more realistic model is required.

We propose an improved model of the system in a very similar form:

$$ T(Q_d, b) = \left( \frac{1}{2} \left[ 1 + \text{sgn}(C_{1h} - C(y(x), V, Q_d)) \right] \right) $$

where $C(y(x), V, Q_d)$ is a function representing a distributed capacitance of the device whose mechanical part has the form of continuous structure from fig. 2. Here the spatial distribution $y(x)$ is a function of the applied voltage $V$ and the dielectric charge $Q_d$.

B. Charging and Discharging of the Dielectric: Dynamics

At this stage we have introduced the dielectric charge $Q_d$ and linked it with the effective voltage $V_{eff}$ given by (1). There are three most commonly used semi–empirical charging models that can be found in literature (see review given in [6]) and also other works [7], [8]):

Model A (single exponential):

$$ Q_d(t) = A_0 + A_1 \exp(-t/\tau) $$

Model B (multiple exponentials):

$$ Q_d(t) = A_0 + \sum_{n} A_n \exp(-t/\tau_n) $$

Model C (stretched exponential):

$$ Q_d(t) = A_0 + A_1 \exp \left[ (-t/\tau)^\beta \right] $$

where $0 < \beta < 1$

where the coefficients $A_i$ and the characteristic times $\tau_i$ are to be determined from fitting of experiment data.

C. Improved Fitting of Experimental Data

In order to extract the realistic dynamics $Q_d(t)$ from experimental data, the following method is employed. In experiment, a capacitive MEMS devices was stressed by a constant voltage (either $V^+$ or $V^-$) over a long interval of time. The dielectric charge accumulates and causes the change of the effective voltage $V_{eff}(t)$ according to (1). The devices ‘sees’ this drift of $V_{eff}(t)$ and the capacitance of the device $C(t)$ also drifts with time. In a certain sense, a ‘Capacitance-Voltage’ characteristic $C(V_{eff})$ is indirectly measured in this experiment, though the exact change of $V_{eff}(t)$ is unknown and the aim of the fitting is to find it. However, with an improved mechanical model, we can calculate the analytical C-V curve for a device with known physical parameters for arbitrary range of the applied voltage. By comparing the experimental $C(V_{eff})$ and the analytical $C(V)$ we find what voltage causes the corresponding change in the capacitance. The charge now is $Q_d = [V_{\text{applied}} - V_{\text{analytical}}] \cdot C_d$. Figure 3 shows the result of the above fitting procedure for the experimental data for a MEMS device from [6]. The solid line shows the extracted experimental data $Q_d(t)$ and the other lines show interpolation of this data by the three different models.

III. DEVELOPMENT OF THE IMPROVED MODEL

Since we introduced the improved discrete-time mapping in the form (3), the function $C(y(x), V, Q_d)$ and the distribution $y(x)$ must be defined and found. Below we describe how to find the distribution $y(x)$.

A. Discretization of the Governing Equation

The deflection of an elastic beam for a given applied voltage is described by the Euler–Bernoulli equation [9]:

$$ \rho \frac{\partial^2 y}{\partial t^2} = -E I \frac{\partial^4 y}{\partial x^4} + F_{el} $$

where $\rho$ is the density of the beam, $E$ is the Young’s Modulus, $I = bh^3/12$ is the moment of inertia, $h$ is the thickness of the beam, $b$ is the width of the beam and $\ell$ is the length of the beam. The force that acts on the beam

$$ F_{el} = \frac{1}{2} \left( \frac{b h^2 V^2}{(g - y + \frac{\ell}{2})^2} \right) $$

is an electrostatic force per unit of length. Here $V$ is the applied voltage, $\varepsilon_0$ is the vacuum permittivity, $\varepsilon_d$ is the relative permittivity of the dielectric, $g$ is the gap distance between the up electrode and the dielectric and $y_d$ is the thickness of the dielectric layer.

For a given voltage $V$, the beam will reach a steady-state distribution $y(x)$. The time required to reach it is very fast.

Fig. 2. Schematic view of a suspended bridge and a cantilever typically used as the mechanical structure in capacitive MEMS varactors and switches.

Fig. 3. Extraction and fitting of the experimental data $Q_d(t)$. Here $\zeta_i$ are the coefficients of exponentials and $\tau_{ci}$ are the characteristic time constants.
since the device operates in air. This allows us to neglect the

time-dependent term in eq. (4). Therefore,

\[ EI \frac{\partial^4 y}{\partial x^4} = F_{el} \]  
(6)

Let us use the following normalized quantities [10]: \[ \hat{y} = y/y_m, \]

\[ \hat{x} = x/l, \quad \hat{V} = \sqrt{(\epsilon_0 d F_e)/g}, \quad \gamma = y_d/g \epsilon_0d \] \text{and} \[ \hat{F}_{el} = V^2/(2\epsilon_e(1-\hat{y}^2+\gamma)^2). \]

Considering the Taylor expression for the fourth-order derivative and introducing \( n \) discrete nodes in the beam domain we obtain a finite difference scheme for equation (6)

\[ y_i = \frac{(\Delta x)^4}{6} \cdot (F_{el} + 4y_{i+1} + 4y_{i-1} - y_{i+2} - y_{i-2}) \]  
(7)

where \( \Delta x = l/(n-1) \) and \( i = 1, 2, \ldots, n \). Here and later the “hat” symbols are omitted.

For the clamped–clamped beam shown in Fig. 2a, both ends are fixed and the boundary conditions are [10]:

\[ y(0) = y(L) = y'(0) = y'(L) = 0 \]  
(8)

or equivalently if the variable \( 1 - y \) is considered instead of \( y \):

\[ y(0) = y(L) = 1, \quad y'(0) = y'(L) = 0. \]

For the cantilever beam, at the clamped end, the boundary conditions are the same as in previous case. For the free end, there are three cases described in [10]. The following one is used in this paper (a flat configuration):

\[ y(0) = 1, \quad y'(0) = 0, \quad y(P) = 0, \quad y'(P) = 0, \quad y''(P) = 0 \]  
(9)

where \( P \) is the point that separates the part of the beam which touches the bottom electrode from the part that has no contact with it. The corresponding finite differences scheme for a fixed end is

\[ y_1 = 1, \quad y_{-1} = 8y_0 + 8y_2 - y_3 = 0 \]  
(10)

The finite differences equations for the flat configuration are:

\[ -y_{n_p} = 0, \quad -y_{n_p+2} = 0 \]  
(11)

\[ -2y_{n_p-1} - 2y_{n_p+1} + y_{n_p+2} = 0 \]  
(12)

\[ -2y_{n_p-2} + 16y_{n_p-1} - 30y_{n_p} + 16y_{n_p+1} = 0 \]  
(13)

where \( n_p \) is the first node in contact with the bottom electrode (all other nodes after this one are also in contact).

IV. PRACTICAL IMPLEMENTATION OF THE MODEL AND RESULTS

A. Modelling Below Pull-In

The regime below pull-in corresponds to MEMS varactors and positioners. In this case we expect that the improved model will give very similar results to the 1D model proposed in [6]. For applied voltages below the pull-in voltage, two techniques are proposed. The first technique, applicable to clamped–clamped systems, uses an iterative method for equation (7) as described in [11]. The second technique, which is applicable for both clamped-clamped and cantilever systems, uses the Newton-Raphson algorithm to solve the system of \( n + 4 \) nonlinear equations (7) together with the corresponding boundary conditions. Figure 4(a) compares the distribution of the beam for the same parameters and applied voltage calculated employing the two above techniques.
As the charging dynamics is used with evolution of the dielectric charge with time is shown at the bottom. Model A as a function of time and its magnified fragment are shown on the top. The Fig. 7. Control method applied to a MEMS beyond pull-in. The capacitance of boundary condition (10) is fulfilled with a required tolerance. Using Newton’s method for root finding. This repeats until having the first two values, the new guess is extracted by using Newton-Raphson algorithm. The solution gives the distribution of equations is solved again giving the new distribution both below and beyond pull-in voltages.

For a given voltage and for a guessed number \( n_{p,1} \), the system of nonlinear equations (7) together with the boundary conditions (11)-(13) for the right end is solved using the Newton-Raphson algorithm. The solution gives the distribution \( y_1 \). After, the second guess for \( n_{p,2} \) is made, and the system of equations is solved again giving the new distribution \( y_2 \). Having the first two values, the new guess is extracted by using Newton’s method for root finding. This repeats until boundary condition (10) is fulfilled with a required tolerance.

If \( n_{p,0} \) is computed for a given voltage \( V_0 \), the value of \( n_0 \) can then be calculated for any voltage \( V \) using the function \( f(V) = n_{p,0} \cdot \frac{1}{2} \sum n_p \cdot T_0 \leq T \leq T_p \). This function will give real values for \( n_0 \) so these values must be rounded up and \( n_p = \text{round}(n_{p,0} \cdot \frac{1}{2} T_0) \) in integers. For a cantilever beam, a similar approach can be followed [10].

Implementing this approach, we can find the distribution of the mechanical structure for any given \( V \) beyond pull-in. Figure 6 shows the C-V curve of a MEMS device as computed for the parameters of Table I, including voltages below and beyond pull-in. Note that realistic MEM structures change their distributions even beyond pull-in, which cannot be predicted by the simple 1D model. This approach can be used together with the improved model (3) to find the capacitance function \( C(y(x)) \). The control method applied to a structure beyond pull-in is shown in fig. 7 by the example of a clamped–clamped beam. This figure models the experimental example of a MEMS switch under the control method given in ref. [6].

V. CONCLUSIONS

In this paper we have developed system-level modeling of capacitive MEMS devices with a control method which is aimed at fixing the dielectric charge. In modeling, we include all aspects of the system: control method, charging dynamics and realistic models of the mechanical components of MEMS. We have shown that we can simulate the operation of MEMS both below and beyond pull-in voltages.

REFERENCES