HIGH-FIDELITY MEMS SWITCH MODEL

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ABSTRACT

A high-fidelity dynamic model of an electrostatically actuated microswitch is developed for the performance assessment of a membrane-type MEMS switch. The simulation model accounts for multi-physics behaviors involved in the switching action such as structural dynamics, ambient damping mechanisms, and electromechanical coupling effect. The genuine attribute of the present model is accounting contact-bouncing motion between moving switch and a stationary electrode foundation, which takes place before permanent contact is achieved. To do this, a localized Lagrange multiplier method is utilized in nonlinear governing dynamic equation. The simulation model can be used as design tools to improve switch performance such as switching time and actuation energy and reduce switch bounce in future designs.

Keywords: MEMS switch, multi-physics dynamic model, contact motion.

1 INTRUDUCTION

MEMS switches have been used in a wide variety of microwave applications. These switches exhibit several advantages over solid-state semiconductor devices for the following reasons: low loss and small measurable signal distortion since the switching action is accomplished by mechanical contact [1,2]. While various microswitches are currently being developed, their dynamic behaviors are not well understood, especially the contact mechanism between switch-substrate electrode. Once the switch starts to contact, it bounces many times before making a permanent contact. As the switching speed is further increased, this bouncing motion much degrades signal transmission due to long settling time to steady contact. Since the electrostatic force and squeeze-film type damping are extremely sensitive to the change of gap when the gap is very small, it is reported that accurate analysis of contact-bouncing behavior is crucial to get an accurate analyses for switching speed and power consumption [3].

Most conventional switch simulation models often utilize an artificial penalty function or linear spring to model the on-off type contact mechanism [4,5], which is not a physics-based model. In this work, to account for the switch contact motion, a localized Lagrange multiplier method is utilized in nonlinear governing dynamic equation [6], i.e., this simulation model includes finite element model of electrode foundation as well as nonlinear membrane switch. As an advantage of the localized Lagrange multiplier method, we can develop a unified model of pull down-contact-bouncing motion. In addition, in order to describe a high-fidelity switch motion properly, the present simulation model accounts for multi-physics behavior involved in the switching action such as structural dynamics, ambient damping mechanism, and electromechanical coupling effect. Based on the present model, contact behavior and actuation energy are investigated for the actual membrane type MEMS switch.

2 MUTI-PHYSICS MODELING

The switch modeled in this study is shown in Figure 1. The switch is 0.5μm thick, 300μm long and the contact length is 100μm. Since the thickness is small enough compared with the length so that the switch can be regarded as a membrane in this case. The membrane consists of aluminum alloy with perforations to reduce squeeze-film type ambient damping during its operation. The membrane switch is electrostatically actuated by the capacitance change at the gap between the membrane and the stationary electrode underneath. Typical pull-down voltage is 31 volts with gap of 2 μm.

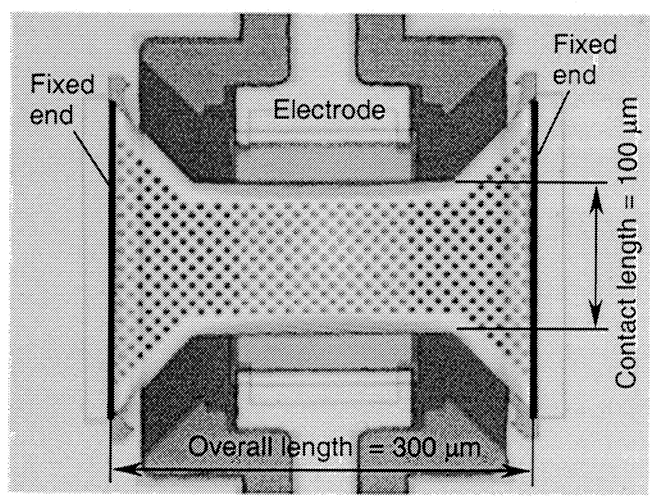

Figure 1: Layout of membrane microswitch (courtesy of Raytheon).

The switch simulation model can be partitioned into several sub-models accounting for different physics such as membrane structural dynamics; ambient damping mechanisms including squeeze-film type and viscous dampings ($F_{damping}$); electrostatic force (F_{el}); and, contact force between the membrane and the electrode ($F_{contact}$). Integrating all the sub-models, we can write the global governing equation of motion of the membrane switch in a discretized form as

$$M_m \ddot{u} + C_m \dot{u} + K_m u = F_{el} + F_{damping} + F_{contact} \qquad (1)$$

where u is deformation of the switch; M_m, C_m and K_m are mass, damping and stiffness matrices of the membrane; Detailed modeling procedures for each term in equation (1) are described in the following subsections.

2.1 Membrane Structural Dynamics

The membrane structural properties are modeled by finite element method. Structural properties of the membrane such as mass, damping, and stiffness matrices are nonlinear functions with respect to deformation u due to the elongation of the membrane. Since the stiffness of the membrane is sensitive to the tension change of the membrane, this nonlinear behavior should be accounted for to obtain adequate structural model. The nonlinear structural properties can be expressed as

$$M_m = M_m(u),\ C_m = C_m(u),\ K_m = K_m(u) \qquad (2)$$

Figure 2 shows the finite element elements of the membrane with fixed ends obtained from MATLAB structural dynamics toolbox and those of the substrate electrode underneath obtained from ANSYS 5.7.

2.2 Electrostatic Force / Ambient Damping

Electrostatic force exerted on the membrane is continuous over the electrode area. To effect the continuous force into a discretized finite element model in equation (1), we assume that the electrode gap over the membrane is piecewise uniform with patches in the vicinities of the finite element nodal points as illustrated in Figure 3. With this assumption, the electrostatic force component can be written as [3]

$$F_{el,i} = -\frac{\varepsilon_0 A_i V^2}{2(g_0 + g_1 + u_i)^2} \quad \text{for } i = 1,2,\ldots,n. \qquad (3)$$

where ε_0 is permmivity of air; V is actuation voltage; g_0 is initial gap (2μm); g_1 is thickness of dielectric layer (0.2μm); u_i and A_i are the displacement and patch area corresponding to the i-th node. Dominant damping forces involved in the present membrane switch are squeeze-film damping and viscous damping forces. With the discretization of the continuous deformed shape of the membrane shown in Figure 3, the squeeze-film damping force component can be written as [7]

$$F_{damping,i} = -\frac{\mu L_i W_i^3}{(g_0 + u_i + \lambda)^3}\frac{du_i}{dt} \quad \text{for } i = 1,2,\ldots,n. \qquad (4)$$

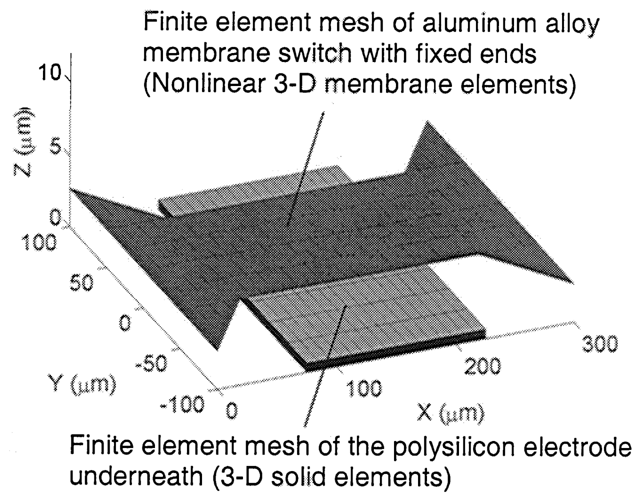

Figure 2: Finite element models of nonlinear membrane and substrate electrode.

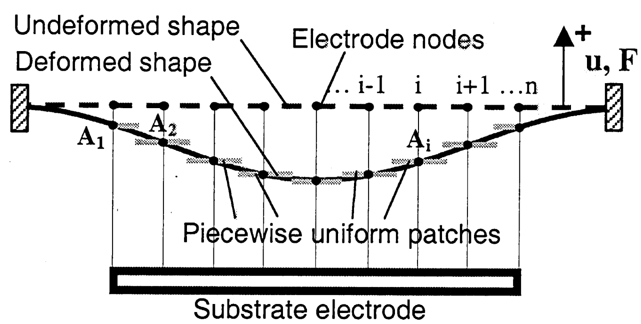

Figure 3: Discretization of continuous deformations into piecewise uniform patches on the membrane.

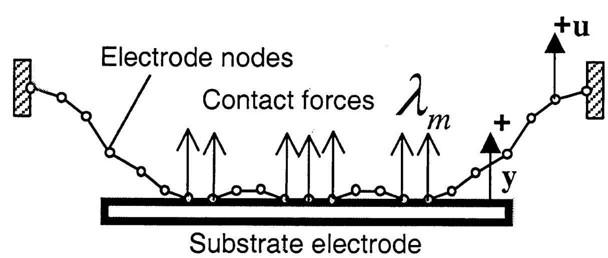

Figure 4: Contact force generation at the contact points between the membrane and substrate electrode.

In similar way, the viscous damping force can be written as

$$F_{viscous,i} = -k_A \mu A_i \frac{du_i}{dt} \text{ for } i = 1,2,\ldots,n. \tag{5}$$

where L_i and W_i are the length and width of the i-th patch; λ and μ are mean-free path and viscousity of air; k_A is shape factor that accounts for the perforation rates.

2.3 Contact Force Model

When the membrane contacts to the substrate electrode as illustrated in Figure 4, reaction forces are generated against the moving membrane at the contact points, which yields repeated impact-bouncing motions. A unified model of the switch motion including global pull-down motion plus impact-bouncing can be developed by adequately introducing the contact force term in governing equation (1). In the present study, the contact force is modeled by a localized Lagrange method [6]. The governing equations of the membrane (6) and the substrate electrode (7) including contact forces can be written using Lagrange multipliers λ_m and λ_e as

$$M_m \ddot{u} + C_m \dot{u} + K_m u + B\lambda_m = \sum F(u, \dot{u}) \tag{6}$$

$$K_e y + B\lambda_e = 0 \tag{7}$$

where $B = [b_{ij}]$ is a Boolean matrix with b=0 for non-contacting nodes and with b=1 for contacting nodes; and K_e is the stiffness matrix of the substrate electrode. The displacements of the membrane u and the electrode y satisfy geometric compatibility at the contact; and, the lagrange multipliers, which is physically the contact forces acting on each substructure, satisfy force equilibrium as

$$B^T[u - y] = 0 \text{ and } \lambda_m + \lambda_e = 0 \tag{8}$$

By substituting equation (8) into equations (6) and (7), we can get the contact force acting on the membrane as

$$F_{contact} = \lambda_m = -(F_{bb})^{-1} B^T u \tag{9}$$

where $F_{bb} = B^T K_e^{-1} B$

3 SIMULATION AND DISCUSSION

Multi-physics simulation model is developed for the actual membrane switch in Figure 1. To investigate the effect of the present contact model on the bouncing motion, we compared the present simulation result with the previous work that uses 'rigid' substrate with artificial restitution coefficient to account for the bouncing motion [5]. Figure 5 shows the impact-bouncing motions after pull-down for two cases. For the present result, one can see the penetrations of the membrane into the substrate, which makes the membrane bounce against the electrode. After the permanent contact is achieved, the present switch motion converges to the static equilibrium state caused by the electrostatic force and the stiffness of the electrode. On the other hand, the previous model exhibits unrealistic number of impact-bouncing motions before getting into the permanent contact.

To minimize the impact-bouncing motion, the time-profile of the actuation voltage can be optimized. Figure 6 (a) shows the original switch motion in which a single step actuation voltage is used; and, the optimized switch motion resulted from a multi-step actuation voltage profile. The optimized result exhibits an accelerated switch motion in the early stage whereas it shows a decelerated motion before contact, which in turn yields small impact-bouncing motion after contact as shown in Figure 6 (b). The optimized bouncing motion lasts about 0.02μsec after pull-down time (1.58μsec) until permanent contact is achieved whereas it lasts about 0.1μsec in the original case.

One of the notable effects of the impact-contact motion on the switch performance is reliability: large impact motions yield in turn mechanical damage or heat generation to the membrane, which possibly reduce the life-time of the switch. To investigate the energy delivered to the moving membrane by the impact behavior, the energy changes versus time are plotted in Figure 6 (c). The total actuation energy delivered to the switch by the external voltage excitation is larger in case of the original voltage profile in around 0.8×10^{-4} μJ compared with the optimized one.

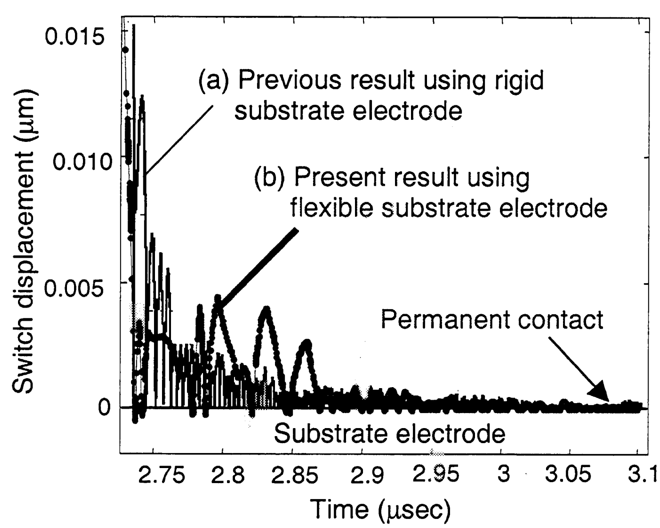

Figure 5: Membrane switch motions at the center after pull-down. (a) Previous model: substrate electrode is modeled as a rigid body and an artificial restitution coefficient is allowed to account for the bouncing motion. (b) Present model: substrate is modeled as a flexible structure by finite element method.

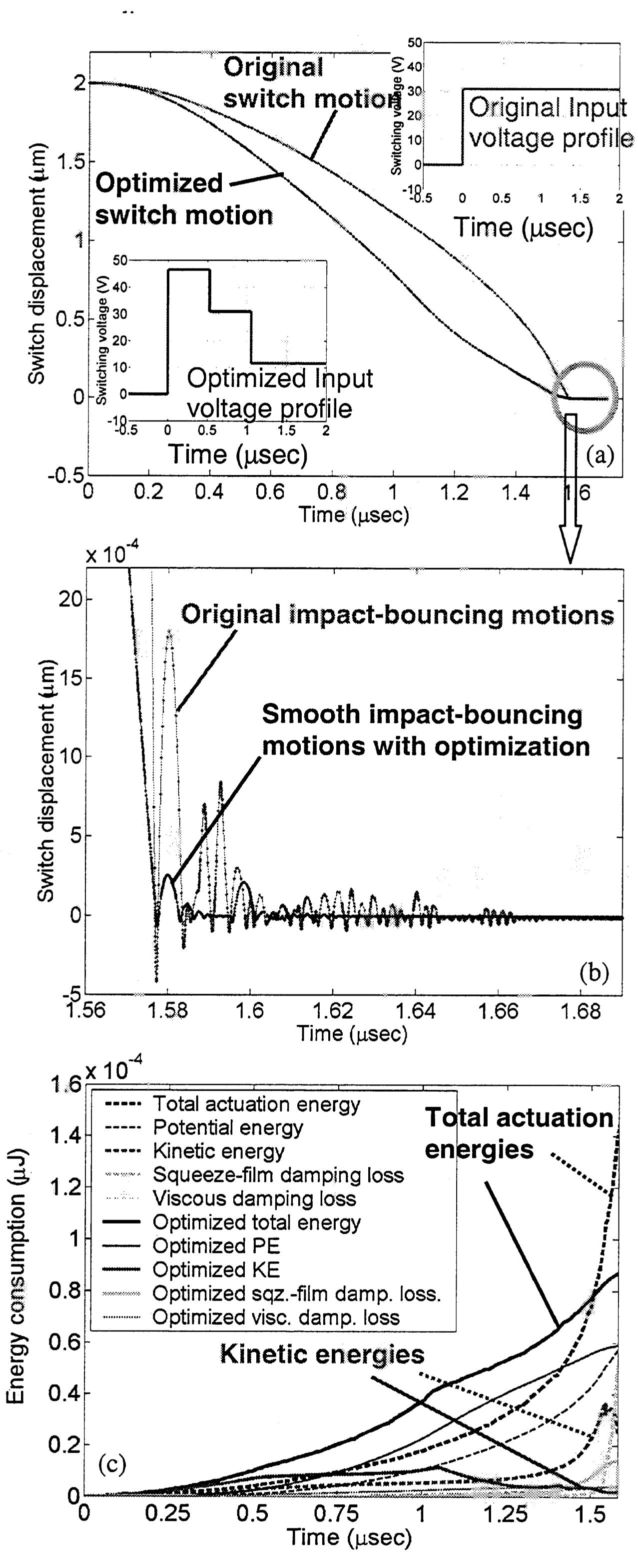

Figure 6: Simulation results of the membrane switch. (a) motions of membrane at the center versus time for different actuation voltage profiles; (b) Corresponding impact-bouncing motions after contact; (c) Energy changes involved in the switch motion versus time.

The actuation energy difference is mostly contributed by the kinetic energy difference before contact: the original motion lost the kinetic energy of 0.4×10^{-4} μJ per cycle and this amount of energy yields impact and damage of the membrane. On the other hand, the kinetic energy lost for the optimized one is very small (0.02×10^{-4} μJ per cycle) since the speed of the membrane is smoothed before contact.

4 CONCLUSIONS

A high-fidelity dynamic model of a nonlinear membrane microswitch is developed for the performance evaluation of the MEMS switch. The model accounts for multi-physics behaviors such as structural dynamics, ambient damping mechanism including squeeze-film and viscous dampings, and electromechanical coupling effect. In the model, the flexibility of the substrate foundation is accounted for by a Lagrange multiplier method to depict a realistic contact motion of the switch. The simulation result from the actual membrane switch reveals that the bouncing motion can give rise mechanical damages to the switch whose amount of energy is 0.4×10^{-4} μJ per cycle. The impact-bouncing motion of the switch is shown to be smoothed with the modification of the actuation voltage profile. The present high-fidelity model can be used as design tools to improve switch performance such as switching time and actuation energy and reduce switch bounce in future designs.

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