Combined Multiphysics and RF Macromodels for Electrostatic Actuated Micro-Electro-Mechanical Switches

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Micro-electro-mechanical switches are devices based on micromachining technologies, used to allow or block the propagation of radio-frequency (RF) signals in various applications. Their transition from one RF state to the other involves combined field analysis such as structural, electrostatic (in the case of an electrostatic actuation), squeeze-film damping phenomena. This contribution refers to a methodology to extract a macromodel that includes both the multiphysics behavior and the RF behavior of an electrostatically actuated switch. The extraction is based on the results obtained from various simulations carried of device-level models, with finite element method (for the multhiphysics part) or finite integration technique (for the RF part). The novelty with respect to our previous work is that now damping phenomena is included, the macromodel being able to extract not only S-parameters for the RF stable states and static pull-in voltage, but also dynamic pull-in voltage, switching time and pull-out voltage.

Index Terms—**Computational modeling, Coupled analysis, Macromodels, Model order reduction, MEMS Switches**

I. Introduction

A Typical RF switch with an electrostatic actuation contains an elastic bridge over a coplanar waveguide line (Fig. 1). The design of this device focuses not only on the RF performances in its stable states, but also on other relevant quantities related to its switching from one stable state to the other. The investigation of the latter aspects needs multiphysics simulations since several physical effects (mechanical motion, air damping, electrostatic actuation) come together [1], [2].

The goal of this paper is to obtain a combined macromodel, that includes both the multiphysics behavior and the RF behavior of the switch. This is a continuation of [3], the novelty being the addition of squeeze-film damping phenomena into the coupled structural-electrostatic part of the mixed multiphysics -RF macromodel. This is essential for an accurate computation of the commutation time.

II. Combined multiphysics and RF macromodels

In order to change the stable state of the switch (e.g. from up to down), an electric voltage has to be applied between

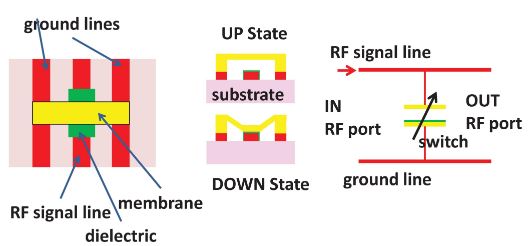

Fig. 1. Typical capacitive RF switch of bridge type. Left - The movable part (membrane, or bridge) is placed transversely with respect to a coplanar wave guide RF signal line. Middle - The switch has two stable states: up and down; Right - The switch is used in an RF circuit, being able to allow the signal to pass (if it is in the up state), or block it (in down state).

the central line and the membrane. The electric force that appears moves the mobile part until the mechanical contact is achieved; when the voltage is zeroed, the system moves back to the initial position due to the elastic forces in the membrane. During the movement, there is also a damping force due to the relative moment of the mobile plate with respect to the gas that surrounds it. The most simple reduced order model appropriate for this coupled structural-electrostatic-fluid formulation corresponds to the equation of motion of a mobile plate of a parallel plate capacitor, suspended by a spring, when an actuation voltage is applied between its plates, which can be seen as a nonlinear time invariant system described by the following two equations, where a more general (i.e. cubic) dependence of the elastic force with respect to the displacement is considered.

$$\left\{ \begin{array}{rcl} \frac{\mathrm{d}z}{\mathrm{d}t} & = & v, \\ m\frac{\mathrm{d}v}{\mathrm{d}z} & = & F_{\mathrm{ES}}(u,z) - kz - k_s z^3 - bv. \end{array} \right. \quad (1)$$

If the applied actuation voltage is not high enough, the electrostatic force might be not high enough to ensure the contact, but only to change the gap between the armatures. If the actuation voltage is higher than a certain value called *pull-in voltage* V_{pi} then the mobile part collapses on the fixed part. The pull-in voltage is an important characteristic of a switch and therefore, it has to be caught by a multiphysics macromodel. When solving a set of static multiphysic coupled simulations, corresponding to increasing values of the applied actuation voltage, an instability occurs when the pull-in voltage is reached.

In order to extract the macromodel's parameters, a set of coupled finite element analysis simulations for several applied voltages $u \leq V0$, were carried out. Equation (1) suggests the following *extraction algorithm for the effective lumped* *coefficients of the macromodel*:

1) Do coupled static (structural-electrostatic) numerical simulations (e.g. FEM) for increasing values of the actuation voltage u. Record position $z(u)$ and electrostatic energy $W_{\mathrm{ES}}(u)$;
2) Compute the dependence of the switch capacitance $C(z) = 2W_{\mathrm{ES}}/u^2$ on the membrane displacement. Approximate the dependence $1/C(z)$ with a first order least square approximation $c_1 z + c_2$.
3) Compute the dependence of the electrostatic force $F_{\mathrm{ES}}(z)$ on the displacement by using the generalized force theorem $F_{\mathrm{ES}}(z) = 0.5u^2 \mathrm{d}\,C(z)/\mathrm{d}z$. Since the simulations at step 1 were static, this electrostatic force is equal to the elastic force that acts on the membrane.
4) Do a cubic polynomial least square approximation of the dependence found at step 3 in order to find k and k_s.
5) Do a structural modal analysis and from the fundamental frequency ω compute the effective mass $m = k/\omega^2$.
6) Do coupled transient analysis (structural-electrostatic-squeeze film) for a step actuation voltage. Record position $z(t)$ and electrostatic energy $W_{\mathrm{ES}}(t)$;
7) Compute dependence of the capacitance with respect to the position $C(z)$ and approximate it with an expression $1/(c1z + c2)$; Compute the electrostatic force $F_{\mathrm{ES}}(z)$ by using the generalized force theorem;
8) Compute velocity $v(t) = \mathrm{d}z/\mathrm{d}t$ and acceleration $a(t) = \mathrm{d}v/\mathrm{d}t$;
9) Compute damping force $F_{\mathrm{damping}} = F_{\mathrm{ES}} - F_{\mathrm{elastic}} - F_{\mathrm{inertial}}$, where F_{elastic} uses the effective stiffness coefficients found at step 4 and F_{inertial} uses the effective mass found at step 5.
10) Do a first order least square approximation of the damping force dependence with respect to the velocity and compute the effective damping coefficient.

The SPICE circuit that synthesizes equation (1) is shown in Fig. 2 and the result of its static simulation (in the LTSpice simulator), shown in Fig. 3 agrees very well with the FEM simulation (with COMSOL), especially if the cubic dependence of the elastic force with respect to the displacement is considered. The RF part of the macromodel is shown in Fig. 4. It consists of transmission line parts and lumped circuit elements.

The full paper will show the validation of the macromodel that includes the squeeze-film damping by using dynamic simulations of the multiphysics FEM model and mixed reduced order macromodel and will discuss the advantages and the limitations of this macromodel, as well as the computational effort needed for the extraction. Preliminary analysis showed that in cases when the relative pressure in the squeezed film becomes important the linearization of Reynolds equations fails. On the other hand, the top of the plate exhibits mild pressure variations and sustains consistent vortex structures with magnitudes in a very large spectrum.

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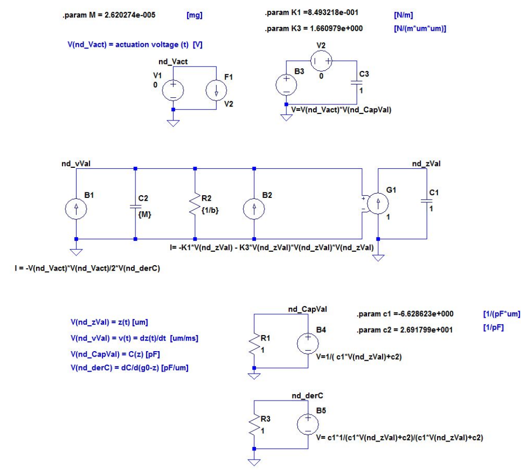

Fig. 2. Equivalent SPICE multiphysics macromodel. The "currents" flowing through this model are forces. The displacement in μm is the voltage at node `nd_sVal` and is used by the source B2 to provide the elastic force. The velocity in μm/ms is the voltage at node `nd_vVal`. The capacitance of the switch is the voltage at node `nd_CapVal`. The derivative of the capacitance with respect to the gap is the voltage at node `nd_derC` and is used by B1 to provide the electrostatic force. The damping is modeled by a conductance b.

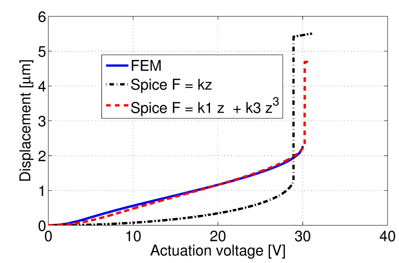

Fig. 3. Static simulations: FEM vs. SPICE equivalent macromodel.

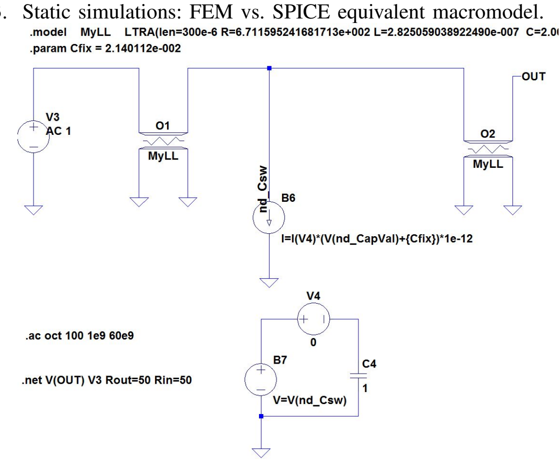

Fig. 4. Mixed macromodel: the RF part, the switch model is a current source controlled by the capacitance value that is taken from the multiphysics part (voltage at node `n_CapVal` in the multiphysics part of the schematic).

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