Automatically Generated and Experimentally Validated System-Level Model of a Microelectromechanical RF Switch

M. Niessner*, G. Schrag*, G. Wachutka*, J. Iannacci** and B. Margesin**

* Institute for Physics of Electrotechnology, Munich University of Technology
Arcisstrasse 21, 80290 Munich, Germany, niessner@tep.ei.tum.de
** MemSRaD Research Unit, Fondazione Bruno Kessler
Via Sommarive 18, 38050, Povo di Trento, Italy

ABSTRACT

We present a computationally efficient multi-energy domain coupled system-level model of an electrostatically actuated RF MEMS switch exposed to squeeze film damping. The physically-based model is systematically derived and calibrated on the basis of a hierarchical modeling approach. The model shows excellent agreement with measurements. Especially coupling effects, that are the increased damping and the spring softening whilst actuation, are correctly reproduced by the model. This demonstrates the power of our modeling approach and, in particular, the predictiveness w.r.t. "real world" experiments. Furthermore, the automatically generated model is suitable for direct implementation into standard circuit simulators.

Keywords: RF MEMS switch, macromodeling, multi-energy domain coupling, mixed-level simulation

1 INTRODUCTION

In the past decade, microelectromechanical systems (MEMS) have been extensively explored with a view to applications in the field of radio frequency (RF) circuits. Microelectromechanical switches employed for the routing of RF signals, for instance, exhibit better performances compared to other concepts because of their low insertion loss and very good voltage standing wave ratio [1]. A key prerequisite for the routine use of RF MEMS switches as standard circuit elements is the availability of computationally efficient, but yet physically-based and, thus, predictive simulation models that describe their operational behavior within a design framework which is easily accessible to circuit designers and enables them to include such models in the design process directly at circuit level.

In this work, we present a mixed-level model of an electrostatically actuated and viscously damped ohmic RF MEMS switch, which provides an accurate physical description of the device behavior and is suitable for direct implementation into standard circuit simulators.

The geometry of the RF MEMS switch analyzed in this work is depicted by the white light interferometer image in fig. 1. The electrostatically controllable device is fabricated using surface micromachining technology [2]. The switch consists of a movable gold membrane suspended above a fixed ground electrode through four straight beams. The membrane on the scale of 140μm x 260μm x 5μm is perforated with square holes having a side length of 20 μm. The fixed ground electrode acts as actuation electrode of the switch and consists of several lateral fingers that are connected in parallel. By applying a voltage to the structure, the suspended membrane can be deflected vertically towards the ground electrode. As the voltage is increased, pull-in occurs and the membrane snaps towards elevated contact surfaces (cp. fig. 2). In this way, an ohmic contact is closed and RF signals are able to pass through the signal path.

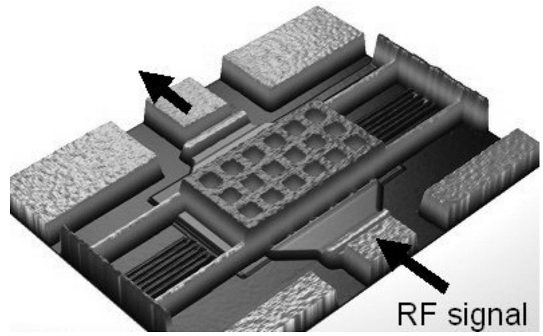

Figure 1: Measured 3D profile of the undisplaced RF MEMS switch. The measurement was performed using white light interferometry.

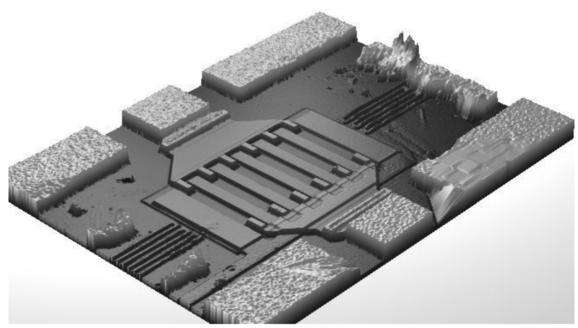

Figure 2: Measured 3D profile of the electrodes and the elevated contact surfaces underneath the membrane. The suspended membrane has been removed to carry out this measurement.

2 MODELING AND CALIBRATION

The coupled multi-energy domain model of the switch is derived on the basis of the hierarchical modeling approach as reported in [3]. Starting point of the modeling procedure is the decomposition of the device into tractable subsystems. In the case of the RF switch, this is the mechanical subsystem represented by the perforated membrane and the four flat suspension springs, the electrostatic subsystem, this is the electric field which is confined by the perforated membrane and the actuation electrode, and, third, the fluidic subsystem comprising the ambient atmosphere that exerts damping forces on the moving parts of the structure. In a second step, physically-based macromodels for the subsystems are formulated in terms of conjugated variables, commonly known as "across"- and "through"-quantities. Finally, the three subdomain macromodels are interlinked to form a coupled system-level model of the device, represented as a generalized Kirchhoffian network coded in one of the commonly used hardware description languages (e.g. Verilog-A), so that the model can be directly implemented within a standard circuit simulator. A detailed description of modeling procedure for each subsystem is given in the following subsections.

For the mechanical subsystem a reduced-order model is derived applying the modal superposition technique. To this purpose, the mechanical substructure, i.e. the membrane and the four suspension beams, is initially modeled by finite elements in order to extract the basic eigenmodes, the discretized device geometry and further parameters of the device. Residual stresses originating from the manufacturing process are taken into account by adjusting the undamped fundamental eigenfrequency of the FEM model to measured data. To this end, the response of the switch to an actuation by a voltage square wave (see fig. 5) was measured and analyzed. Since an electrostatic actuation voltage shifts the natural eigenfrequeny of a mechanical structure significantly due to the spring softening effect, the undamped eigenfrequency is determined from the transient "off-response" ($V_{act} = 0V$) of the structure in order to exclude this effect (see fig. 6, lower graph). The extraction is carried out by performing a mean square fit of the measured data w.r.t. a damped sinusoidal function with the undamped eigenfrequency and the linear damping factor as fit parameters. Thus, the undisturbed eigenfrequency of the prestressed device has been determined to 14.7 kHz and accordingly adjusted in the mechanical submodel.

In a second step, the electrostatic subsystem is investigated. In order to derive a reliable compact model describing correctly the electrostatic forces due to the striped electrode structure (see fig. 2), small lumped parallel plate capacitor elements are introduced at those nodes of the discretized membrane geometry, which are located right above the electrode fingers. This results in an electrical network of a large number of differential plate capacitors in parallel, but with locally varying gap. In a next step, the total capacitance of this network is calculated for various modal shape functions and amplitudes of the bridge and we obtain the capacitance of the entire system as function of the modal amplitudes. This constitutes a more compact and efficient description of the electrical effects which can be implemented directly as a single lumped element model into a system-level description of the device. The electrostatic model is validated by measuring the static deflection of the membrane at different biasing voltages and comparing it to simulated results obtained with the electromechanically coupled model. As the mechanical model has been already calibrated by exploiting the information on the natural eigenfrequency of the system, this measurement then exclusively delivers information on the electrostatic forces acting on the bridge and on potential need for further model calibration steps. Consequently, it turned out that especially the parasitic capacitances due to the measurement setup have to be taken into account in order to get a good agreement with the measurement (cp. fig. 3).

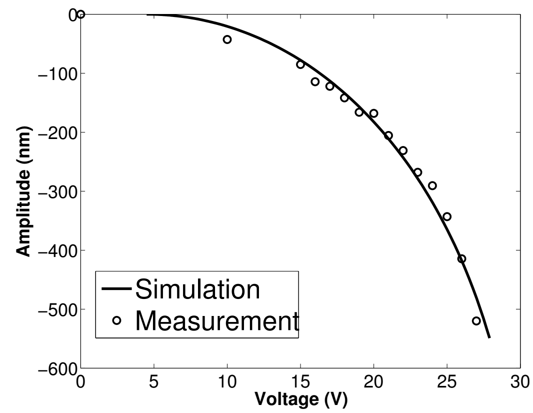

Figure 3: Measured and simulated static deflection of the membrane as caused by different applied voltages. A calibrated electromechanical model was used for the simulation.

For modeling the viscous damping effects acting on the moving parts of the device, the mixed-level approach described in [4] is applied. Under the assumption of small Reynolds numbers and sufficiently large ratios of structure width to fluid film thickness, the fluidic model employs the Reynolds equation instead of the much more complicated Navier-Stokes equations. By spatially discretizing the Reynolds equation, we obtain a fluidic finite network governed by pressure differences and mass flow rates as conjugate variables. At the boundary nodes (i.e. along edges or perforation holes) the finite network is supplemented by fluidic resistances to account for the flow rates through the boundary [5]. One ma-

NSTI-Nanotech 2009, www.nsti.org, ISBN 978-1-4398-1784-1 Vol. 3, 2009

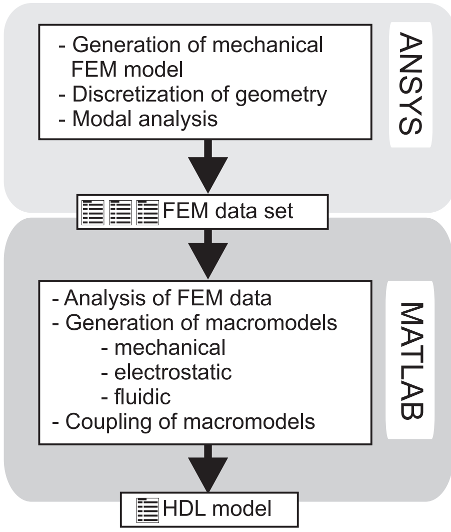

Figure 4: Workflow for the generation of mixed-level macromodels employing an on-purpose developed MATLAB-based modeling toolbox.

jor advantage of employing a mixed-level model in this case amongst others is that it enables a direct and flexible implementation of the spatially varying gap height underneath the switch originating from the structured actuation electrode. Since the respective nodes can be supplied directly with the correct gap, no overall constant effective fluid film thickness has to be estimated, and the viscous damping can be calculated very exactly without a noticeable loss of accuracy. Since this fluidic mixed-level model is also based on a generalized Kirchhoffian network formulation it can be easily connected to the other submodels of the system.

The practical use of the above-described model generation techniques is strongly facilitated by a dedicated MATLAB-based modeling toolbox. It enables the automated generation of mixed-level macromodels from given FEM device (sub-)models and the respective eigenmodes, if needed [6]. Models for the mechanical, fluidic, and electrical domains on different descriptive levels are already implemented in the toolbox and can be selected as modules according to the specific requirements. The resulting mixed-level macromodels are coded in an analog hardware description language. The workflow for the generation of the models employing the toolbox is illustrated in fig. 4.

3 RESULTS FROM FULLY COUPLED SYSTEM SIMULATION

The fully coupled mixed-level macromodel which has been generated applying the mixed-level toolbox is now validated against measurements. To this end, the switch is electrostatically actuated with a periodic square wave (25V "on-state" and 0V "off-state", see fig. 5). The

source	quality factor
measurement ("off-repsonse")	$11 \pm 7\%$
measurement (frequency sweep)	$10.7 \pm 10\%$
simulation ("off-repsonse")	11.25

Table 1: Comparison of quality factors.

response of the switch results in two step responses: the "on-response" (see fig. 6, upper graph), i.e. the damped oscillation of the membrane when the voltage is turned on, and the "off-response" (see fig. 6, lower graph), i.e. the damped oscillation of the membrane when the voltage is turned off. The "on-state" voltage was chosen to 25V, far enough from the pull-in voltage of 29.5V, so that the membrane is deflected only about 350nm (= 12% of the entire gap) towards the electrode in the static case. The advantage of the measuring procedure described above is that the different segments of the overall response deliver specific conclusions on the validity of the different submodels.

During the "off response", for example, the voltage is turned off, the deflected membrane relaxes to its original position, and the dynamic behavior of the system is merely determined by the coupled mechanical-fluidic subsystem. Since the mechanical model is already calibrated by adjusting the fundamental eigenfrequency of the structure, the "off-response" enables the validitation of the physically-based fluidic model. This can be done by comparing the quality factors calculated from the mean square fit on the measured "off-response" in section 2, from the $3dB$-bandwidth of a measured frequency sweep and from the simulated "off-response" (see table 1). A deviation of only 5% between the measured quality factors (center values of 11 and 10.7) and the simulated value, leads us to the conclusion that the fluidic model works correctly and can be considered as validated, even without any recalibration of the single fluidic submodels.

The "on-response", however, is determined by the full coupling between electrostatic, mechanical, and fluidic energy domain. Since the electro-mechanical coupling has been already calibrated by static measurements (cp. fig. 3) and the fluidic submodel has been validated by investigating the "off-response", the "on-response" allows us to evaluate if the coupling effects are correctly implemented within the model. The first coupling effect is the electrostatic spring softening. Once a voltage is applied to the electrostatic system, it couples with the mechanical system by decreasing the spring constant and thus the eigenfrequency of the system. The second coupling effect is that the actuation decreases the gap between the ground and the membrane so that the fluidic damping is increased. As can be seen in fig. 6 (upper graph), the results from measurements and simulation correspond excellently, so that we can conclude that these two coupling effects are correctly implemented in

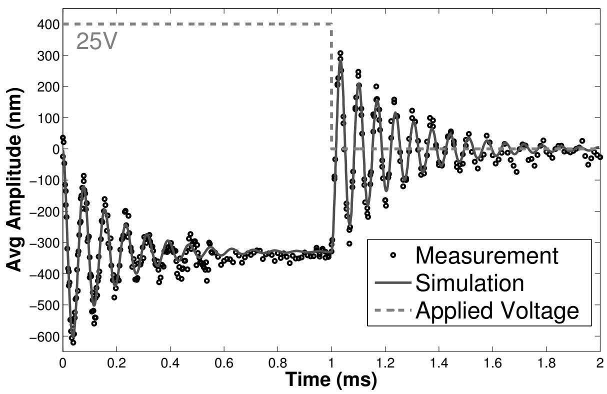

Figure 5: Measured and simulated transient response of the membrane to an electrostatic excitation by a 500Hz voltage square wave (levels 25V and 0V).

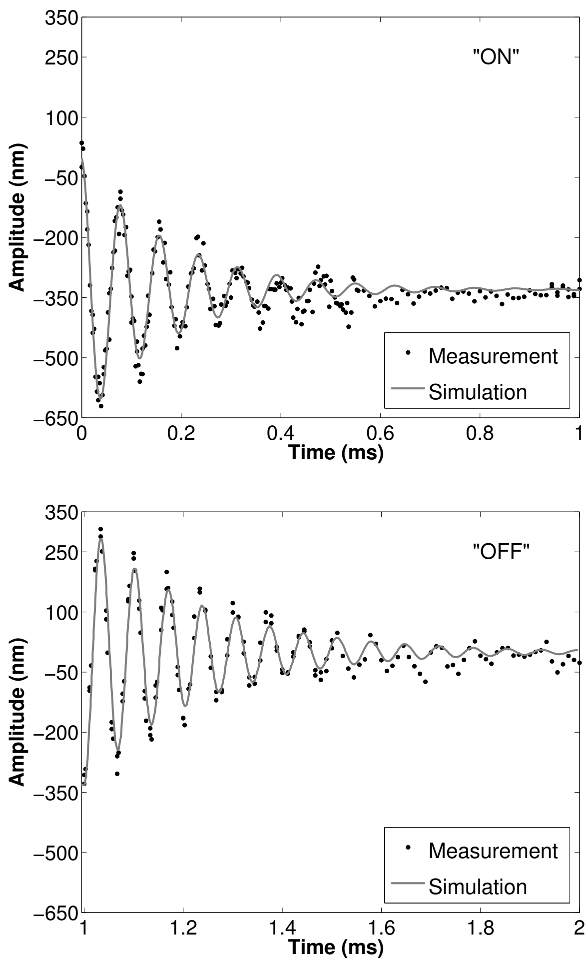

Figure 6: Detailed view of the measured and simulated response of the membrane. **Upper** graph: "on-response" to the voltage step $0V \to 25V$. **Lower** graph: "off-response" to the voltage step $25V \to 0V$.

our model.

It is important to point out that these coupling effects are not necessarily correctly included, especially if the applied models are not physically-based. In [7], a very similar structure is simulated by a model, which is generated by mathematical order reduction techniques and which contains fit parameters. The results reveal that this model is not able to reproduce such coupling effects correctly.

4 CONCLUSION

In this paper, physically-based systematic and transparent modeling methodologies [3] were subsequently applied to derive a mixed-level macromodel of an RF-MEMS switch. In a first step, models of tractable subsystems are formulated and calibrated. In a second step, a full system model is synthesized by coupling the subsystem macromodels together. Generalized Kirchhoffian network theory is used as a framework for the model because it allows for combining different energy domains and different descriptive levels in one unified system model. It was shown that the derived multi energy-domain coupled model is in excellent agreement with measurements. Furthermore, the model correctly reproduces the coupling between energy domains, e.g. the spring softening effect and the increased damping during actuation, while models of RF switches without physically-based description of the gas film damping fail at this point. This demonstrates the power of our modeling approach and, in particular, the predictiveness w.r.t. "real world" experiments.

Future research will focus on the simulation of the dynamic pull-in of the device, especially on a proper treatment of the inherently occurring instabilities and the contact problem.

REFERENCES

[1] V. Varadan, et al., "RF MEMS and their applications", Wiley, Chichester, pp. 118ff, 2003.

[2] Iannacci J., et al., Proc. Memswave 2008, Heraklion, 2008.

[3] Schrag G., et al., Proc. Eurosensors XXII, Dresden, pp. 538-531, 2008.

[4] Schrag G. and Wachutka G., Sensors and Actuators A, 97-98, pp. 193-200, 2002.

[5] Sattler R. and Wachutka G., Proc. DTIP 2004, Montreux, pp. 377-382, 2004.

[6] Niessner M., et al., Proc. IEEE Sensors 2006, Daegu, pp. 915-918, 2006.

[7] Del Tin L., et al., Proc. Transducers 2007, Lyon, pp. 635-638 2007.

NSTI-Nanotech 2009, www.nsti.org, ISBN 978-1-4398-1784-1 Vol. 3, 2009