NON LINEAR COMPACT MODELING OF RF-MEMS SWITCHES BY MEANS OF MODEL ORDER REDUCTION

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Abstract: In this work, a new method is presented for the extraction of low order electromechanical models for dynamic nonlinear simulation of radio frequency (RF) microelectromechanical (MEMS) switches, using model order reduction (MOR). The method is based on a separate modeling of the electrical and the mechanical part of the problem, which are coupled at circuit level. The derived reduced order model includes effects of initial stress in the device materials and enables a substantial speed-up of large signal dynamical analysis. The accuracy of the model has been demonstrated by comparing the simulated and measured dynamic response of a fabricated device.

Keywords: Model Order Reduction, RF MEMS, switches

1. INTRODUCTION

In the last decade, MEMS devices have been demonstrated suitable for signal routing in RF circuits [1]. Due to the complexity of MEMS devices, key requirement for the successful implementation of MEMS based systems is the development of CAD tools for predictive design and optimization of MEMS structures and electronic devices at circuit level [2].

RF switches are mainly operated in large signal dynamic regime. They are characterized by the nonlinear coupling between the mechanical and the electrical energy domain. Device simulation requires therefore a nonlinear dynamic analysis.

Modeling of switches often uses spatial discretization methods to solve the partial differential equations governing the device behaviour. This approach enables a very accurate description of the device, but leads to extremely large models. Their nonlinear dynamic simulation is therefore computationally very expensive and the use at circuit level is excluded.

Various methods have been proposed for compact modeling of MEMS devices with electrostatic actuation. For what concerns switches, mixed-level hierarchical analysis is often used. This is based on the decomposition of the device mechanical structure into atomic elements, which are separately described using matrix structural analysis [3]. Very popular are also global basis function methods that use global basis functions for the discretization of the device PDEs [4].

This paper presents a new approach for extraction of nonlinear compact models of electrostatically actuated MEMS devices. The procedure is based on a separate modeling of the mechanical and electrical part of the problem. The mechanical part of the problem is discretized using the finite element method in ANSYS© and the resulting element matrices are reduced using mathematical model order reduction. Electrostatic forces are integrated in the reduced order model and this is translated in VerilogA and imported in a commercial circuit simulator. An RF capacitive switch is used for model validation. Comparisons between simulation results and the measured dynamic behaviour of the device are presented.

2. RF MEMS COMPACT MODELING

The approach proposed follows the block diagram in Fig. 1. Mechanical and electrostatic domains are modeled separately, using different tools. The mechanical domain of the device is modeled using the finite element program ANSYS. Effects of initial stress in the device material can be included in the mechanical stiffness element matrix by calculation of the stress stiffening matrix [5]. Damping is included in the model as Rayleigh damping. The damping matrix is computed as a linear combination of the stiffness and the mass matrices. If geometrical nonlinearities are neglected, the derived finite element (FE) matrices are linear and can be reduced using linear MOR techniques.

The electrostatic forces acting on the movable conductor of the device are included in the model as nonlinear input forces, which are applied on nodes distributed over the conductor surface. This is divided into N smaller portions. A lumped force is applied to a node n_k at the center of each portion, in its preferential direction of movement x_i. The capacitance C_k between the portion k and the fixed electrode of the device is computed, for its undeformed configuration, using an electrostatic analysis. The entity of each force f_k is then approximated as:

$$f_k = \frac{1}{2} \frac{C_k}{d(d + u_i^k)^2} V^2 \qquad (1)$$

where d is the initial distance between the conductor and the electrode, u_i^k is the displacement of n_k along the direction x_i and V is the voltage applied between the conductor and the actuation electrode. Such an equation is based on the assumption that C_k depends only on the rigid displacement of the portion and not on its deformation. However, this approach is only one of the many possibilities for the description of the electrostatic forces. Other methods can be used, according to the desired degree of accuracy. In particular, more accurate results can be obtained by replacing nodal forces with pressure loads and by computing the capacitance-displacement relation with a series of electrostatic computations.

In order to access the displacements u_i^k, these degrees of freedom are included in the outputs of the mechanical model. Moreover, N load vectors are calculated, each describing a mechanical nodal force applied to n_k along the direction x_i.

The tool MOR for ANSYS allows to read the mechanical element matrices directly from ANSYS binary files and to reduce them using implicit moment matching model order reduction via the Arnoldi algorithm [6]. The compact model is translated into the VerilogA language and electrostatic forces are implemented at this level,

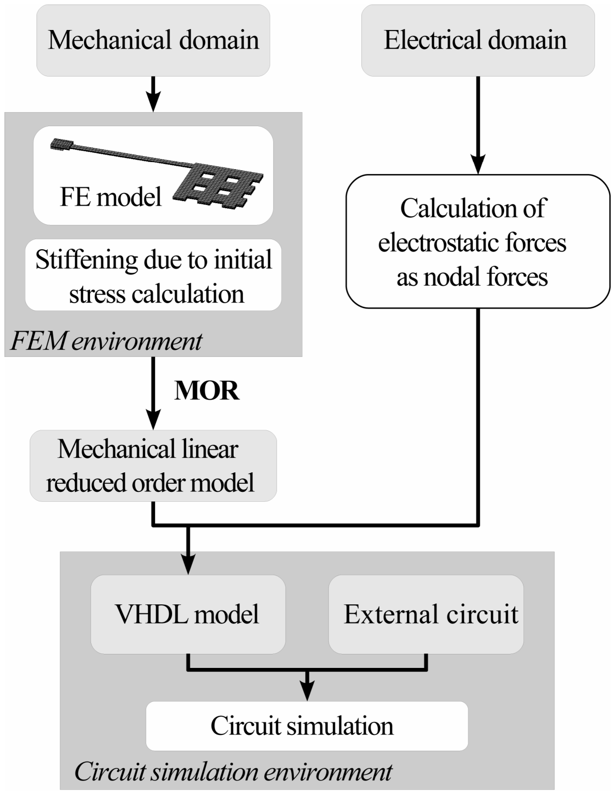

Fig 1::Block diagram of the simulation approach for RF MEMS switch devices.

according to Eq. (1). The number N of nodal forces will correspond to the number of nonlinearities in the reduced model. For its efficient simulation, this number should be kept relatively small.

3. APPLICATION EXAMPLE

The above described procedure is demonstrated for the capacitive switch in Fig. 2. The switch consists of a 5µm thick gold plate suspended over an electrode through 4 straight beams. The electrode is covered by a thin layer of silicon dioxide. Exploiting the device symmetry, only one quarter of the switch mechanical structure is created and meshed in ANSYS, for a total of 45000 degrees of freedom (d.o.f.).

The nodes on the external surface of the plate are grouped into 9 conductors and the capacitance between each conductor and the actuation electrode is computed with an electrostatic analysis. Fringing effects due to the holes in the plate and the finite thickness of the structure are therefore taken into account. Lumped electrostatic forces are computed using Eq. (1).

The device behaviour is affected by a process

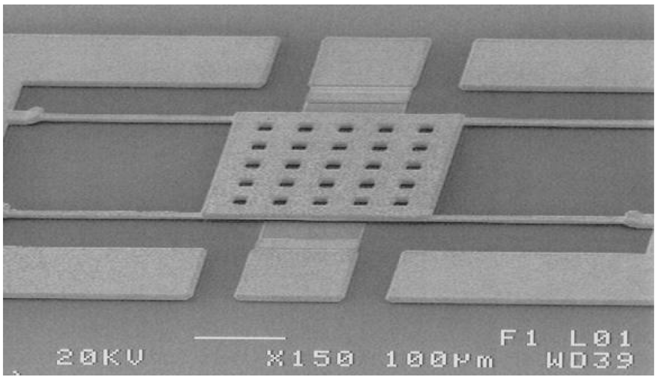

Fig. 2: SEM picture of the capacitive RF switch used in measurements and simulations.

induced tensile stress in the suspended layer, which has been estimated around 30MPa. Such a stress is applied as initial stress in the device membrane during a nonlinear analysis preceding full matrices calculation. A 15 d.o.f. reduced mechanical model with 9 input/output d.o.f. and load vectors is then extracted. The model is translated in VerilogA language, maintaining the Rayleigh damping coefficients as parameters, and is extended with electrostatic forces. The resulting electromechanical model is then imported and simulated with Cadence™ Spectre simulator.

4. SIMULATION RESULTS

The device in Fig. 2 was fabricated at ITC-IRST and characterized optically using an interferometric profilometer (Veeco WYKO NT1100 DMEMS). This allowed to measure the transient mechanical response of the device to different stimuli, which has been used for model validation. Using a stroboscopic LED illumination of the device with a short duty cycle, the profilometer allows to capture the position of the moving device at specific instants in time. At this aim, a periodic signal with the desired waveform is applied to the device. The LED illumination is synchronized with the signal and the device displacement is sampled at a certain phase of the waveform by changing the phase offset between the signal and the light pulse. Since different samples are collected in different periods of the applied signal, the device behaviour should be perfectly periodic to ensure correct measurement.

The simulated and measured dynamic response of the device for a square wave actuation voltage is shown in Fig. 3. The square wave has an amplitude of 15V and a frequency of 1kHz. Circuit simulation results are compared with two sets of experimental data, one extending over the full period of the input waveform with 50µs steps, and the second over the second half period with 5µs steps. In this first dynamic simulation, the values of the damping parameters are chosen so to obtain the best fit between simulation and experimental data. The agreement achieved is very good, especially in the second semi-period of the square wave. The deviation observed in the first semi period can be attributed to the simplified model adopted for damping phenomena. During the first semi-period, the switch membrane oscillates close to the actuation electrode. Thus, damping is higher with respect to the second semi-period and the oscillation frequency of the switch is lower. Such an effect can be captured only if the damping force is dependent from the device position, which is not the case for Rayleigh damping.

The large signal response of the switch has been simulated for a sinusoidal actuation voltage with 10V amplitude and frequency varying from 5kHz to 15kHz. In order to reproduce the measurement conditions, a transient analysis has been performed for each frequency step and the in-phase displacement of the central part of the switch plate has been measured, once the periodic steady state was reached. The damping parameters extracted from the previous dynamical simulation have been used. A comparison between experimental measurement and simulation is given in Fig. 5. Also in this case, the agreement is very good, especially for frequencies above the

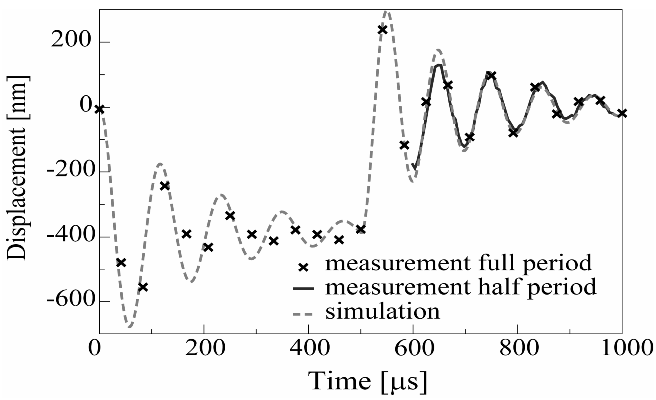

Fig. 3: Switch response to a square wave actuation voltage. Circuit simulation results are compared with two sets of experimental data.

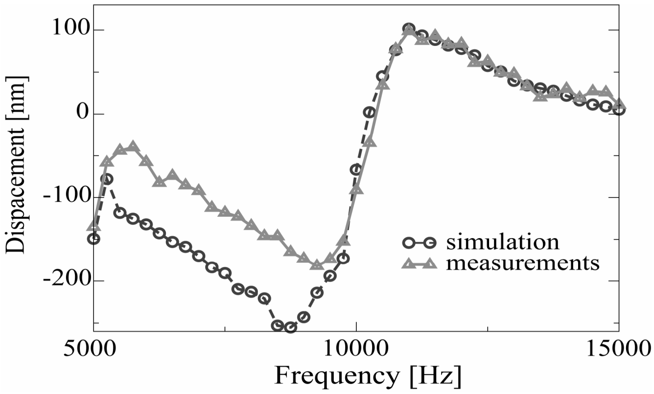

Fig 4: Circuit simulation results and measurements of the large signal response of the switch to a sinusoidal actuation voltage.

switch resonance frequency. It is worth noting that a correct prediction of the device dynamic behaviour would have not been possible without inclusion of initial stress effects.

The computational time needed for the extraction and the dynamic simulation of the model, as in Fig. 4 (2700 time steps), are reported in Table 1. The derivation of the model requires around 600s. The computational cost of the reduction step grows with the number of inputs nodes. This sets another limit to the maximum number of nodal forces for the electrostatic domain description. Simulation of the reduced model can be performed in less that one second while a full system transient analysis would require ca. 1000 seconds for each iteration point.

5. CONCLUSION

In this work, a method is proposed for the extraction of nonlinear compact models for the fast dynamic simulation of electrostatically actuated MEMS at circuit level. The method is based on the separate modeling of the electrical and mechanical domains. A reduced mechanical model, including also pre-stress effects, is automatically derived by applying model order reduction to ANSYS FE matrices. Devices with any geometrical complexity can thus be modeled. Electrostatic forces are implemented at circuit level as nonlinear inputs and can be modeled at the desired level of approximation. Adopting a small number of nonlinear inputs, the extraction and simulation of the derived compact models is fast. Nevertheless, they describe with very good accuracy the device behaviour.

Table 1: Computational times required for the extraction of a reduced order and its dynamic simulation as presented in Fig.3.

Operation	Tool	Time
Initial stress state & element matrices computation	ANSYS	68.1s
Reduced model extraction	MOR for ANSYS	500s
Electrostatic force computation	ANSYS	59.2s
Dynamic simulation	Cadence	660ms

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