Extended Abstracts of the 2010 International Conference on Solid State Devices and Materials, Tokyo, 2010, pp1158-1159

A SPICE-based Multi-physics Seamless Simulation Platform for CMOS-MEMS

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1. Introduction

Multi-physics simulation for MEMS (microelectromechanical systems) is becoming an indispensable tool to comprehend the behavior of the system under test, where electrical and mechanical coupled response should be analyzed simultaneously [1]. In the conventional design procedures, however, micro mechatronics and electronics were designed independently by using separate simulation tools except for a few examples that were limited to small-displacement analysis only [2]. Apart from this, we have adopted an approach to develop a co-solver for the mechanical equation of motion (EOM, $m \cdot \ddot{x} + c \cdot \dot{x} + k \cdot x = F$) by using a circuit simulator, which enables us to perform multi-physics simulation in both small and large signal domains on a single simulator platform [3]. In this late news, we report a SPICE version of such multi-physics solver that is capable of microelectromechanical transient analysis, AC harmonic analysis, and electro-mechanical mixed-signal simulation that can be performed seamlessly with the LSI simulation.

2. Co-solver for Equation of Motion

Figure 1 illustrates the model for a typical electrostatic micro actuator with a pair of parallel plates that are electrically biased to generate electrostatic attractive force

$$F_E = \frac{1}{2}\varepsilon_0 \frac{S}{(g-x)^2} V^2, \qquad (1)$$

where S, V, g, and x are the plate area, the drive voltage, the initial gap, and the displacement of the movable plate, respectively. Mechanical displacement at the equilibrium condition is calculated by equating (1) with the mechanical viscoelastic force

$$F_M = c \cdot \dot{x} + k \cdot x, \qquad (2)$$

where c and k are the damping coefficient of the dash pod and the spring constant of the suspension, respectively. In our work, these components are visually presented as sub-circuits as shown in Fig. 2. The EOM co-solver module inserted between the viscoelastic suspension and the electrostatic actuator is programmed to calculate the resultant displacement and velocity as a function of the impinging forces, in a similar manner as an analog computing circuit.

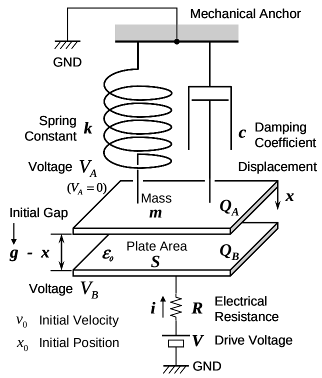


Fig. 1 Schematic model for a parallel-plate electrostatic micro actuator

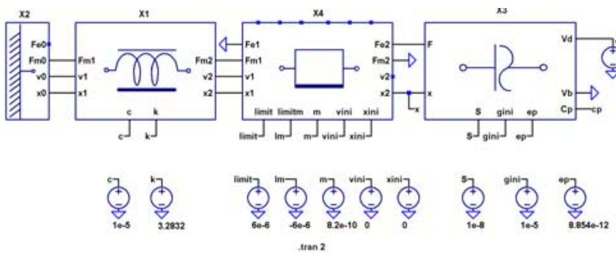


Fig. 2 LTspice simulation circuit for transient analysis.

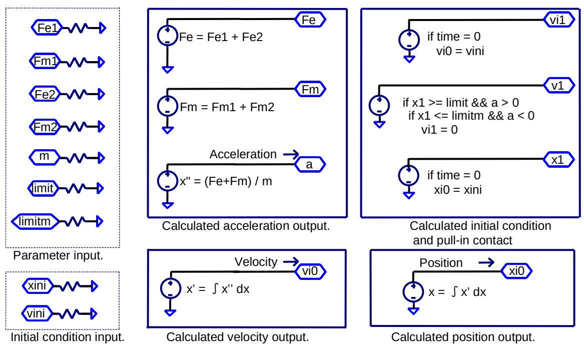
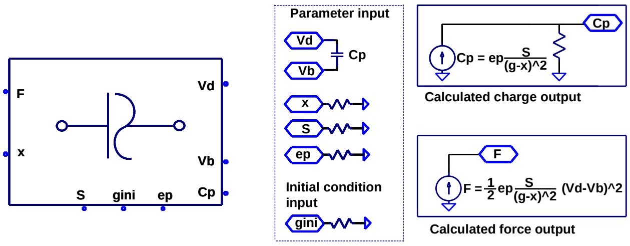


Fig. 3 Generalized sub-circuit model for the EOM co-solver

Figure 3 is the kernel of the EOM co-solver that reads in the multiple signals such as the actuator's drive force and suspension's restoring force. Mechanical equation of motion is a second-order differential equation, and it can be processed in an integral form through a series of integrators using two electrical capacitors that read electrical current input and return the integration results as voltage output. This mathematical operation has been implemented by using a nonlinear dependent current source of LTspice that could be programmed with an algebraic equation. LTspice is also capable of if-then-clause conditioning branch, which is used to judge the mechanical contact.

In a similar manner, the actuator's force (Eq. (1)) and the suspension's viscoelastic restoring force (Eq. (2)) are modeled by the equation-defined current sources as shown Fig. 4(a) and (b), respectively.



(a) (b)

Fig. 4 Equivalent circuit models for (a) parallel plate actuator and (b) viscoelastic suspension.

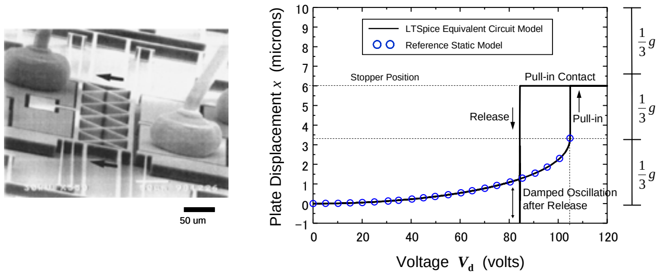
3. Multi-physics Simulation Results

The newly developed multi-physics simulator was cross-checked with a known electrostatic micro actuator, shown in Fig. 5(a), as a static verification model. This device was made of an SOI (silicon-on-insulator) and processed by the DRIE (deep reactive ion etching), and it exhibited electrostatic pull-in phenomenon at 130 V, where the movable electrode was brought into the stopper position before colliding with the drive electrode. Dimensional parameters such as suspension length, width and electrode gap were measured in the SEM (scanning electron microscope) and passed as an argument to the sub-circuit modules. As shown in Fig. 5(b), the typical hysteresis curve of electrostatic actuation has been clearly reproduced by the simulation, and the calculated pull-in voltage of 105 V agreed well with the experimental value, considering the fabrication error of the suspension width of +/-0.5 microns.

For dynamic mode analysis, we ran the program to model an electrostatic actuator inserted in the Colpitts oscillation circuit as shown in Fig. 6. Electrostatic actuator is known to behave as an electrical inductor at its resonance frequency like a quartz oscillator, and a self oscillation at 6.9 MHz was observed in this model. So far as the authors know, this is the first demonstration of a SPICE-based multi-physics MEMS simulation using the equation-defined nonlinear current source for actuator modeling.

3. Conclusions

We have developed a SPICE-based multi-physics simulator for MEMS that could handle both electromechanical and electrical simulation on a single platform. Equivalent circuit model for micromechanical device was directly synthesized from its analytical mathematic model by using an equation-defined nonlinear current source. Unlike most MEMS simulators, our methodology has higher degrees of freedom in adapting to various MEMS devices, as compared in Table I. Seamless extension to mask design layout is under development.



(a) (b)

Fig. 5 Example (1) / transient analysis results of parallel-plate electrostatic actuator: (a) SEM image of sample actuator and (b) displacement-voltage curve.

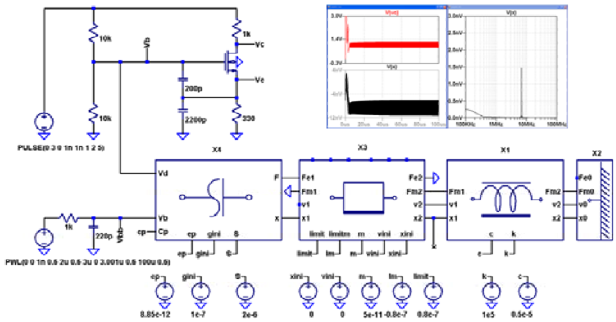


Fig. 6 Example (2) / multi-physics simulation on electrostatic silicon resonator in the Colpitts oscillation circuit.

Table I Comparison of MEMS multi-physics simulations

	Conventional Separated Design		Multi-Physics Simulation		
	MEMS	LSI	Ref [1]	Ref [2]	This Work
MEMS mechanical simulation capability	FEM	---	Limited types of MEMS module provided.	Equation defined analytical model	Equation defined analytical model
Electrical Circuit Simulation Capability	---	Spice	Yes but requires net-list generation	Yes	Yes
Simulation Time	Lengthy		Fast	Fast	Fast
Parametric Analysis (Parameter Sweep)	No	Yes	Yes	Yes	Yes
Extension to RF Analysis	No	Yes	No	Yes	Yes
Deviation Analysis	No	Yes	No	Yes	Yes
Multi-physics Analysis	Yes but needs extra analysis module.		No	Yes	Yes
Mask Design Layout Capability	On separate circuit-only CAD environment.		No	No	Under Development

Acknowledgement

The authors would like to thank Mr. Kazuhiko Komatsu with NTT-AT for technical discussion.

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