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A Spice-based Multi-physics Simulation Technique for Integrated MEMS

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***Abstract*—This paper presents an LSI-designer friendly and handy simulation technique for integrated MEMS (microelectromechanical systems) using a Spice-based circuit simulator. Microelectromechanical components such as electrostatic actuators and elastic springs are interpreted into lumped equivalent circuit models that could be co-solved by an equation-of-motion module with peripheral electrical circuits.**

Keywords-component; MEMS, microelectromechanical systems, multi-physics simulation, equivalent circuit

I. Introduction

MEMS or microelectromechanical system(s) is a field of fusion, where more than two domains of physics are involved in one tiny device; for instance, a micro electrostatic actuator requires the knowledge of both electrical and mechanical engineering, and a silicon microphone needs analytical skills in acoustic simulation as well as in electrical circuit design. It is therefore a natural consequence that the MEMS engineers need multi-physics simulation tools to comprehend the overall behavior of an electromechanical system in a top-down manner [1]. In the conventional development of MEMS, however, three dimensional (3D) mechanical deformation or motion has been the priority target of understanding, and hence the simulation tools available for MEMS development have been mostly based on the 3D FEM (finite element method). They are quite useful to simulate and display the complicated mechanical behavior. Nonetheless, 3D simulation makes it difficult to deal with the electrical circuit simulation tools, as the sampled data points becomes an enormously larger number with the complexity of the device mechanism.

Figure 1 illustrates the typical procedure for MEMS actuator analysis based on the FEM. One would usually start with the two dimensional photomask patterns to extend a three dimensional mesh model. In one path of mechanical analysis, the mesh model is put into a mechanical solver to calculate the three dimensional deformation of structure as a function of applied force or torque, where a mechanical transfer function is synthesized as a look-up-table. In the electrical simulation path, on the other hand, the identical mesh model is used to calculate the electrical capacitance as a function of electrode displacement, which is then converted into the electrostatic force (or torque) as a function of the electromechanical boundary conditions. These two data sets are merged into one to co-solve the mechanical deformation under a given voltage by using another simulation tool called co-solver. A drawback of this method is, however, one may need to repeat the entire procedure from the beginning every time the MEMS structure dimensions are modified, and it takes large amount of computation power of PC to prepare the mechanical and electrical matrices.

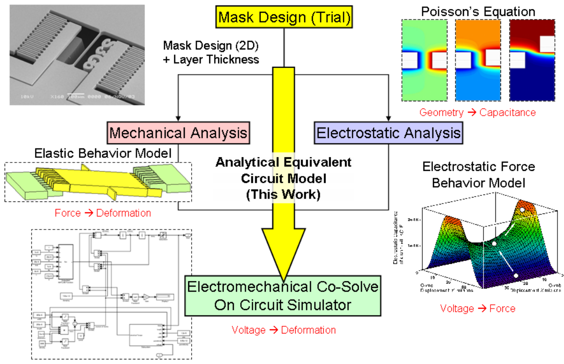

Figure 1. MEMS simulation flow

In contrast to this, we use a very simple method to simulate the behavior of a MEMS actuator or sensor by using an electrical circuit simulator as a platform for multi-physics analysis [2]. We parameterize a micro actuator with its dimensions to express the output force or torque by using a lumped equivalent circuit model. We also have developed a solver for the mechanical equation of motion in the same manner as an analog computing. As a result, all the elements of micro actuator are represented by a lumped parameter model such as a suspension, actuator plates and a mass.

In this paper, we present the approach of converting a micro mechanical device into an electrical equivalent circuit model using the LTspice simulator. As a verification sample, we show the electrostatic parallel plate actuator to discuss the static simulation accuracy. We also give three-body oscillator model as a verification model of a harmonic analysis. Finally we demonstrate the multi-physics simulation on an electrostatic actuator that acts as a mechanical resonator in the feedback loop in an oscillator circuit.

II. Co-Solver for Equation of Motion

A. Electrostatic Parallel Plate Actuator

Figure 2 illustrates an analytical model for a typical electrostatic actuator with a pair of parallel plates that are electrically biased to generate the electrostatic attractive force

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

where S, V, g, and x are the plate area, applied voltage, initial gap length, and the mechanical displacement of the movable plate, respectively [3]. Mechanical displacement of the plate is calculated by equating (1) with the restoring force

$$F_M = c \cdot \dot{x} + k \cdot x, \tag{2}$$

described by the Hooke's law, where c and k are the damping coefficient of a dash pod and the elastic constant of a spring, respectively. In our work, these components are visually presented as a sub-circuit as shown in Fig. 3. The solver for equation of motion (EOM, $m\ddot{x}+c\dot{x}+kx=F$) is inserted between the viscoelastic suspension and the electrostatic actuator to calculate the resultant displacement and velocity by comparing the electrostatic force and the mechanical restoring force under a given mass m; within these blocks, an electrical feedback circuit has been made to numerically seek for the equilibrium solution.

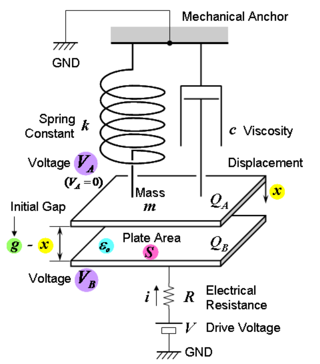

Figure 2. Analytical model for electrostatic parallel plate actuator

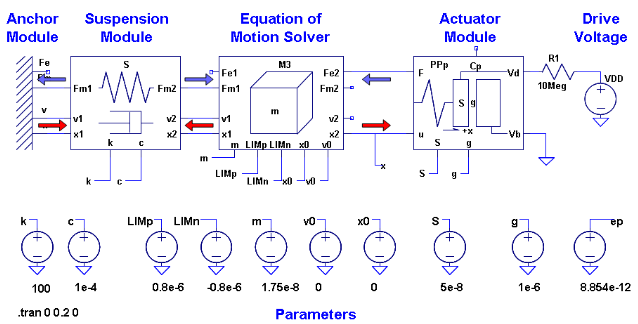

Figure 3. Spice-based MEMS simulation block diagram

B. Equation of Motion Co-solver Module

Figure 4 shows the kernel of the EOM co-solver module that reads in the multiple signals such as actuator's output force and the suspension's restoring force. Mechanical equation of motion is a 2nd order differential equation, and hence it can be converted into an integral form through a series of mathematic integrators. As an equivalent circuit implementation, we used nonlinear dependent current and voltage sources of LTspice that could be programmed by using an algebraic equation [4]. LTspice is a handy tool for this particular simulation method, as it has a mathematic integration as a built-in function. The sub-circuit has been designed to read in the electrostatic force and mechanical restoring force; after adding them, the module calculates the acceleration by dividing it by the mass m. Velocity and displacement can be found by mathematically integrating the time sequential data of acceleration through the nonlinear dependent voltage sources that have been programmed to integrate the inputs. Parameters such as the mass m, initial displacement and velocity, and the stopper positions are passed to the module as argument voltages.

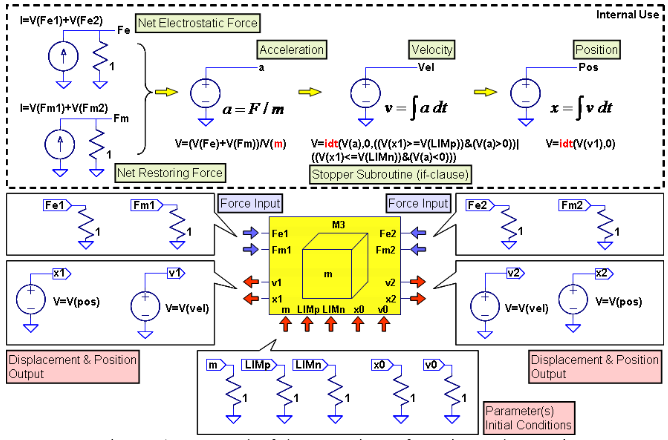

Figure 4. Kernel of the equation-of-motion solver unit

Because the voltage and the current sources of LTspice can be programmed by an equation, any analytical model can be converted into an equivalent circuit model so long as it is described by an equation, no matter what physics it is based on. LTspice is also capable of handing an if-then-clause branch, which is useful to model a mechanical contact. In Fig. 4, all the input ports are terminated with an electrical resistor of 1 Ohm to convert the signal into voltages that are cross-referenced by the labels declared in the module.

C. Electrostatic Parallel Plate Module

The equation model (1) for the electrostatic parallel plate can be converted into an equivalent circuit model of LTspice as shown in Fig. 5. The module has been designed to read in the differential voltages applied to the two electrodes and the plate displacement x to synthesize the electrostatic force in the form of (1) by using the structural parameters such as S and g as an argument passed to the module. The dielectric constant is defined as an internal constant within the module and referenced in the numerical calculation of the output force. The module has also been programmed to express the inductive charge appearing on the drive electrodes as a result of voltage application; this model is indispensable to describe the electromechanical coupling of the micro actuator with the electrical circuit, particular when it is used as an electrostatic sensor or resonator.

D. Suspension Module

The suspension module shown in Fig. 6 is designed to read in the displacement and velocity measured on the both sides of the dash-pod suspension and then to calculate the restoring force, using c and k as an argument programmed in voltage. The sign of the restoring force is flipped on the left- and right-hand side of the module to express the direction of the force.

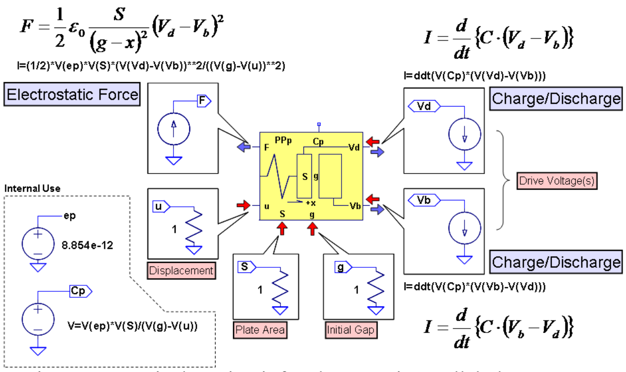

Figure 5. Equivalent circuit for electrostatic parallel plate actuator

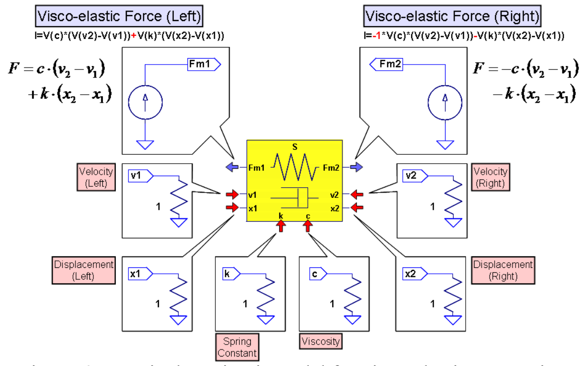

Figure 6. Equivalent circuit model for visco-elastic suspension

E. Anchor Module

The anchor module is simply designed, as shown in Fig. 7, to terminate the output current from the suspension module into the electrical ground. It also has a function to give a static ground potential to the suspension module to interpret the mechanically fixed suspension.

In this simulation approach, both the electrostatic force and mechanical restoring force are expressed in constant electrical current, for it can be simply added to the EOM module by connecting the wires. On the other hand, displacement and velocity are expressed in constant electrical voltage, as it is convenient to distribute the constant value from the EOM module to the peripheral suspension and actuator modules. As a whole, the modules work together in a feed-back circuit form to calculate the equilibrium displacement and velocity as a function of drive voltage to the actuator module.

III. MULTI-PHYSICS SIMULATION RESULTS

A. Pull-in Instability of Electrostatic Parallel Plate Actuator

The developed simulator has been cross-checked with the analytical solution of an electrostatic parallel plate actuator, which is known to have strong nonlinear behavior in its static displacement. Figure 8 compares the analytical results (dots) with the numerical simulation results (curve). With increasing the drive voltage, the movable plate is observed to move toward the fixed electrode due to the electrostatic force. When the displacement has come to the 1/3 of the initial gap, the movable plate is found to trip to close the gap, after which the plate is brought into contact with the mechanical stopper to avoid the electrical short circuit. This phenomenon is known as the electrostatic pull-in, where the electrostatic attractive force exceeds the mechanical restoring force. With decreasing the voltage, the plate is released from the contact state.

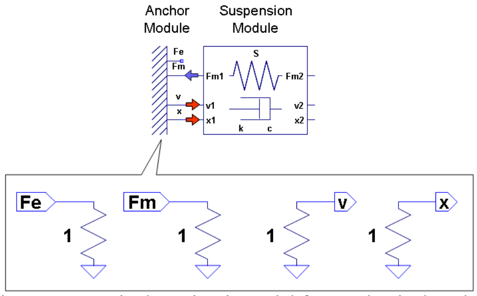

Figure 7. Equivalent circuit model for mechanical anchor

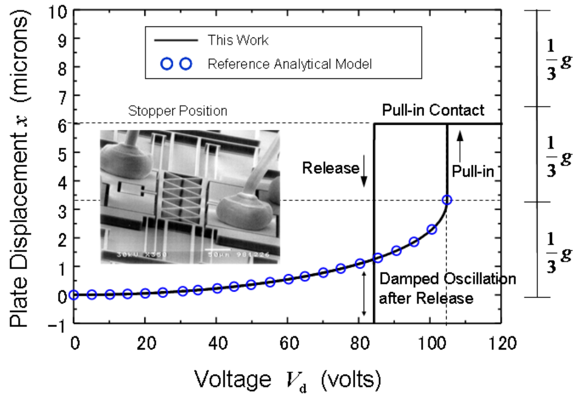

Figure 8. Simulation results of electrostatic parallel plate actuator

Unlike the conventional analytical model, where the simulation is only good until the pull-in moment, the developed simulation model has been found to reproduce the entire hysteresis loop including the electrostatic pull-in and the release. The pull-in effect is widely used in electrostatic actuators such as digital mirror device and grating light valve, and hence a MEMS simulation tool is evaluated by the handling capability of it. The benefit of our approach is that the simulation is performed on an electrical circuit simulator, and therefore it possible to combine the mechanical analysis with an electrical driver circuit, for instance, to optimize the driver circuit design.

B. Harmonic Analysis

We also have tested the developed simulation tool for harmonic analysis using the three-body oscillator as shown in Fig. 9(a). This is a classic model for the harmonic oscillator theory, and it is known to have three fundamental modes with a simple ratio in between the oscillation amplitude. By using the EOM module to represent the three pieces of mass connected with four identical springs, we develop a block diagram model as shown in Fig. 9(b). Thanks to the AC simulation capability already prepared in the LTspice simulation environment, we also could demonstrate the mechanical harmonic analysis to extract the resonant angular frequency as well as the normalized amplitude as shown in Table I. The numerically calculated results are compared with the analytical model at high precision within a 1 % error or less, suggesting that the developed simulation tool is capable of both DC and AC simulation of the mechanical oscillators.

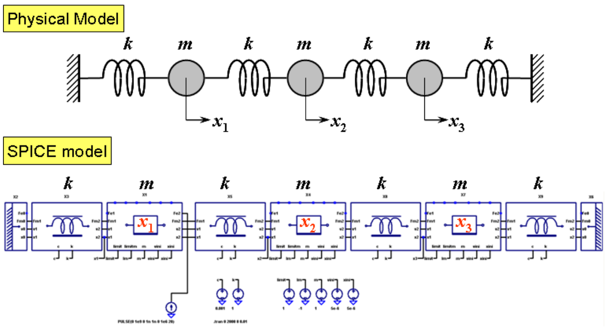

Figure 9. Simulation model for three-body coupled oscillators

TABLE I. SIMULATION RESULTS OF COUPLED RESONATOR

Mode		Amplitude Ratio x_1	x_2	x_3	Resonant Angular Frequency
1	x_1 x_2 x_3	1	$\sqrt{2}$ Theoretical	1	$\omega_1 = \sqrt{2-\sqrt{2}} \cdot \sqrt{\frac{k}{m}} = 0.765\sqrt{\frac{k}{m}}$
		1	1.415 Numerical	1	0.122*(2π) = 0.767
2	x_1 x_2 x_3	1	0 Theoretical	-1	$\omega_2 = \sqrt{2} \cdot \sqrt{\frac{k}{m}} = 1.414\sqrt{\frac{k}{m}}$
		1	0 Numerical	-0.997	0.225*(2π) = 1.414
3	x_1 x_3 x_2	1	$-\sqrt{2}$ Theoretical	1	$\omega_3 = \sqrt{2+\sqrt{2}} \cdot \sqrt{\frac{k}{m}} = 1.848\sqrt{\frac{k}{m}}$
		1	-1.407 Numerical	1.004	0.294*(2π) = 1.847

$(m, c, k) = (1, 0.001, 1)$

C. *Electrostatic Resonator*

To demonstrate the multi-physics simulation capability, we have chosen a MEMS resonator as shown in the inset of Fig. 10. An electrostatic actuator behaves as a capacitive device in the frequency range lower than its resonance. When it is electrostatically excited at the resonant frequency, the device works as an inductive load, because the electrical charges flow 90 degrees out of phase with respect to the excitation voltage. We use the simulation block diagram shown in Fig. 3 and modified it to measure the input impedance of the actuator's electrodes as shown in Fig. 10, where resonance and anti-resonance of the oscillator is clearly observed.

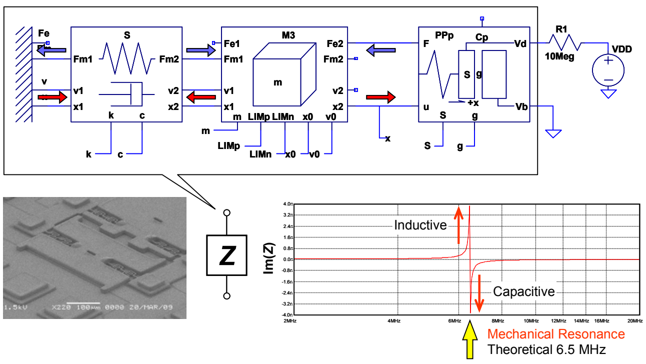

Figure 10. Electrical impedance simulation of electrostatic actuator

As the electrical impedance characteristic is similar to that of a quartz resonator, the MEMS actuator can replace the quartz resonator in the Colpitts oscillation circuit model as shown in Fig. 11. After carefully preparing parameters such as the bias voltages to the transistors and MEMS, the circuit was triggered to start a stable oscillation at the resonant frequency of the actuator, as shown in the transient simulation result in Fig. 11. Many cut and try of parameter setting were needed to tune the circuit for the stable oscillation; this could have not been done by the conventional numerical co-solver based on the combination of 3D mesh model, because the computation time would have been extremely long.

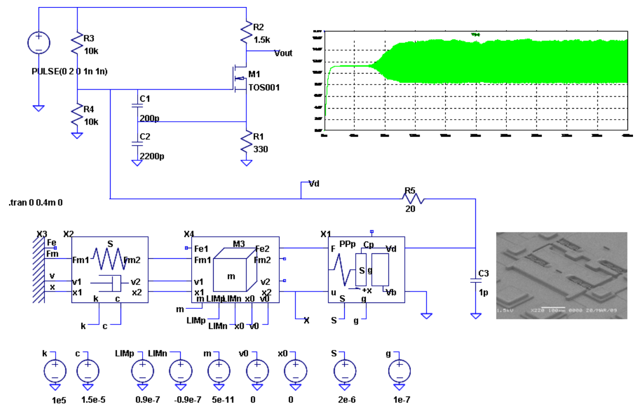

Figure 11. Multi-physics simulation example (silicon resonator)

IV. CONCLUSIONS

In conclusion, we have used a common electrical circuit simulator to build a user-friendly analysis environment for MEMS multi-physics simulation. Our approach takes a lumped parametric model to describe an electromechanical component and interpret it as an electrical equivalent circuit. A key to understand the multi-physics capability is in the kernel co-solver for the mechanical equation-of-motion that has been implemented as a 2nd order integration circuit with feed-back loop with a suspension module and an electrostatic actuator module. Our approach is more straightforward because no labor is needed to extract parameter for the Spice net-list from the mechanical network but what-you-see in the simulation diagram is a direct translation from what-you-have in an actual MEMS design.

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REFERENCES

[1] S. D. Senturia, "Simulation and design of microsystems: a 10-year perspective," Sensors and Actuators, A67, pp. 1-7, 1998.

[2] M. Mita, S. Maruyama, Y.Yi, K. Takahashi, H. Fujita, and H. Toshiyoshi, "Multiphysics analysis for micro electromechanical systems based on electrical circuit simulator," IEEJ Trans., vol. 6, pp. 180-189, 2011.

[3] H. Toshiyoshi, Electrostatic actuation. In Comprehensive Microsystems, vol. 2, Y. B. Gianchandani, O. Tabata, and H. Zappe (eds.), Elsevier: Amsterdam, 2008, pp. 1-38.

[4] T. Konishi, S. Maruyama, T. Matsushima, M. Mita, K. Machida, N. Ishihara, K. Masu, H. Fujita, and H. Toshiyoshi, "A Spice-based multi-physics seamless simulation platform for CMOS-MEMS," in Proc. 2010 Int. Conf. on Solid State Devices and Materials (SSDM2010), The Univ. of Tokyo, Tokyo, Japan, Sept. 22-24, 2010, G-6-5.