Yield prediction in an automotive MEMS application with help of statistical analysis packages SAE J2748

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Abstract

This paper shows a methodology for the yield prediction of Micro Electro Mechanical Systems (MEMS). Variations of process properties during the production of MEMS are considered in system simulations. Yield prediction based on the distribution functions provided by statistical analysis packages SAE J2748 is demonstrated on a capacity based accelerometer system.

Key words: MEMS, statistical distribution, Monte Carlo analysis, yield prediction

1 Introduction

The fabrication of MEMS underlies manufacturing process variations like geometry dimension variations of structures i.e. due to under etching, material property variation i.e. due to doping/temper temperature variations, etc. So the yield depends on the nominal - the optimal – design within its parameter tolerance ranges and distribution functions. Today there is a strong demand on decreasing structure sizes of micro-systems like MEMS. Due to this the tolerance range of the fabrication process decreases too. The production has to become more accurate. The tolerance range of each process step has to be well defined. Running a Monte Carlo simulation of the complete MEMS with realistic variations of the parameters considering their distributions helps to determine the yield of the production.

2 The MEMS model

An accelerometer was chosen as demonstrator for the methodology. Figure 1 shows a scheme of a typical single-axis airbag sensor. A seismic mass m is connected through a meander spring to the housing and so builds a spring-mass-damper system. Conductive plates are attached to the substrate on one side. With the counter plates on the other side attached to the movable mass, they build capacitors. These capacitors change capacitance according to the position of the seismic mass in non-linear relation to an external acceleration applied to the device. The resulting change in capacitance is detected and processed by some connected electronics.

For multi-domain or mechatronic simulations, the hardware description language VHDL-AMS (Very high speed Hardware Description Language – Analog and Mixed Signal) is best suited. With VHDL-AMS, it is not only possible to model and simulate time discrete systems but also to model and simulate systems with time continuous behavior; mixed signal circuits like ADC, DAC, PLL or systems of multiple domains like MEMS, MOEMS, MST, µLab. Furthermore, the language offers constructs to handle discontinuities, like they often occur in mechatronic systems. So this language was chosen for implementing the model of the accelerometer.

The SAE J2748 distribution functions, which are also implemented in VHDL-AMS, are used to provide parameter variations with defined stochastic system functions for the geometrical dimensions of the MEMS structure and its material properties. Furthermore, the same method can be applied to the parameters of the electrical circuit for considering their variations in system simulation.

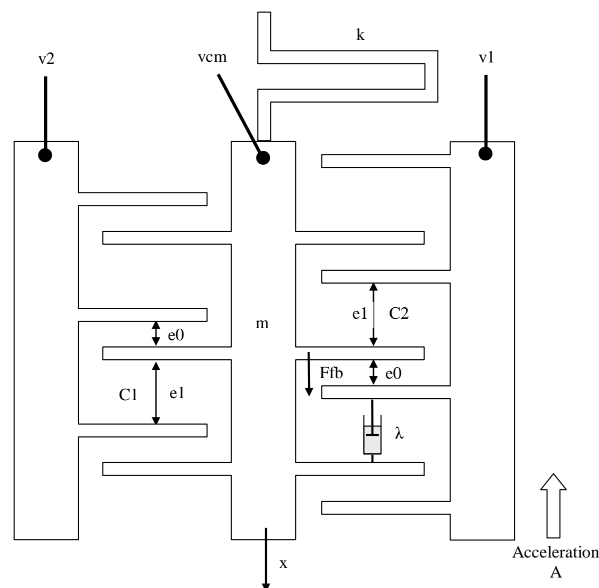

Figure 1: accelerometer scheme, x-axis

2.1 Basic physical effect implementation

The accelerometer is modeled with the basic physical effect approach, i.e. those basic physical effects like the inertia of masses in translational moved bodies, the spring effect of a beam or the electro-static attraction effect between two conductive plates, are modeled in VHDL-AMS and made available in the library EMBLEM-Mecha. To build the model of the complete MEMS device, the effect models have to be connected together (see Figure 2). For this, strict port compatibility has to be used for the "through" and "across" variables (see Table 1).

Type of variable	electrical network	rotational	translational
"through" variable	current i	torque T	force F
"across" variable	voltage v	angle φ	displacement x

Table 1: Variable types of the implemented ports for each domain

The implemented effects are:

- The inertia effect of a translational moved mass. This effect model is instantiated 5 times: for the seismic mass and for the movable and stationary fingers of each of the two capacitors. Equation (1) shows the equation to calculate the mass of a cubic body from the geometrical dimensions and material constants. Equation (2) shows the resulting inertia force of a translational moved mass. With: length l, width w, depth d, specific weight ρ, mass/hole ratio r.

$$m = l * w * d * \rho * \frac{r}{r+1} \tag{1}$$

$$f = m * a = m * \ddot{x} \tag{2}$$

- The spring effect equation to calculate the spring constant of a meander beam from the geometrical dimensions and material constant Emod (elastic modulus of the meander beams) is shown in equation (3). Equation (4) is the corresponding equation for the resulting spring force.

$$k = \frac{d * w^3 * E_{\text{mod}} * n_m}{l^3 * n_b} \tag{3}$$

$$f = k * x \tag{4}$$

- The damping constant d can be determined by the reciprocal value of the quality factor Q, equation (5). Q itself can be calculated with the resonance frequency f0 and the bandwidth B, which can be captured by measurements. The damping force can be calculated with the equation (6); d is the damping constant.

$$d = \frac{1}{Q} = \frac{B}{f_0} \tag{5}$$

$$f = d * v = d * \dot{x} \tag{6}$$

- The capacity of the asymmetrical comb structure can be calculated with help of equation (7) and the geometry dimensions (etch depth d, gap_1, gap_2, overlap length o of the facing fingers and the number of comb fingers n and material parameter (relative permittivity of the material ε_r).

$$C = n * d * o * \varepsilon \left(\frac{1}{gap_1 - x} + \frac{1}{gap_2 + x} \right) \tag{7}$$

- The electrostatic attraction force of the asymmetrical comb drive can be calculated with help of the geometrical dimensions and material constants (etch depth d, gap_1, gap_2, overlap length o of the facing fingers and the number of comb fingers n and material parameter (relative permittivity of the material ε_r) and applied voltage V see equation (8).

$$f = \frac{1}{2} * n * d * o * \varepsilon * V^2 (gap_1 + gap_2) \left(\frac{gap_1 - gap_2 - 2x}{gap_1 * gap_2 + (gap_1 - gap_2) * x^2} \right)^2 \tag{8}$$

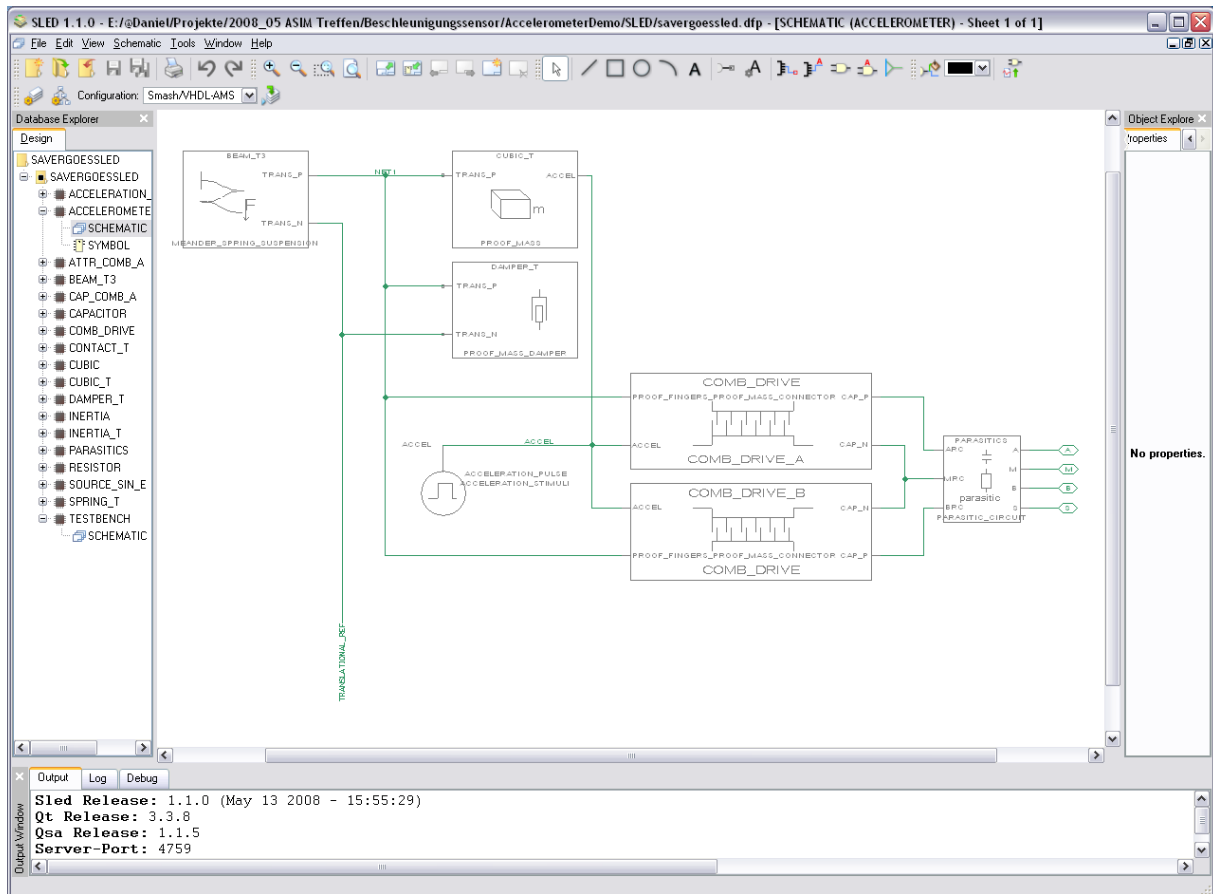

Figure 2: accelerometer scheme, x-axis

2.2 Applying the distributions

The variation of the MEMS structures geometry elements in x,y-direction is applied with Normal (Gaussian) distribution and different tolerances. Since the design of the chosen MEMS structure is insensitive to thickness variation of the structures, no distribution function is applied here. For simplification, the material parameters specific weight ρ, the dielectric constant ε_r and the elastic modulus of the beam E_{mod} are supposed to be well controllable in the process and are considered constant in this simulation. The Normal distribution function of the SAE J2748 packages is applied on the parameters in the accelerometer architecture, which are then passed to the effect model instances through the generic maps.

3 Monte Carlo simulation

The above described model is used to determine the resonance behavior of the MEMS device. For this, the accelerometer model is instantiated in a simple test-bench and a small signal Monte Carlo analysis was initialized. Figure 3 shows the small signal Monte Carlo analysis with 50 random runs. With this simulation, it is possible to detect if the processed accelerators perform in an acceptable range or not. For each of the random runs it is possible to extract the applied device parameters for further design optimizations. This helps significantly to value the fabrication process for an expected yield or if a design optimization becomes necessary.

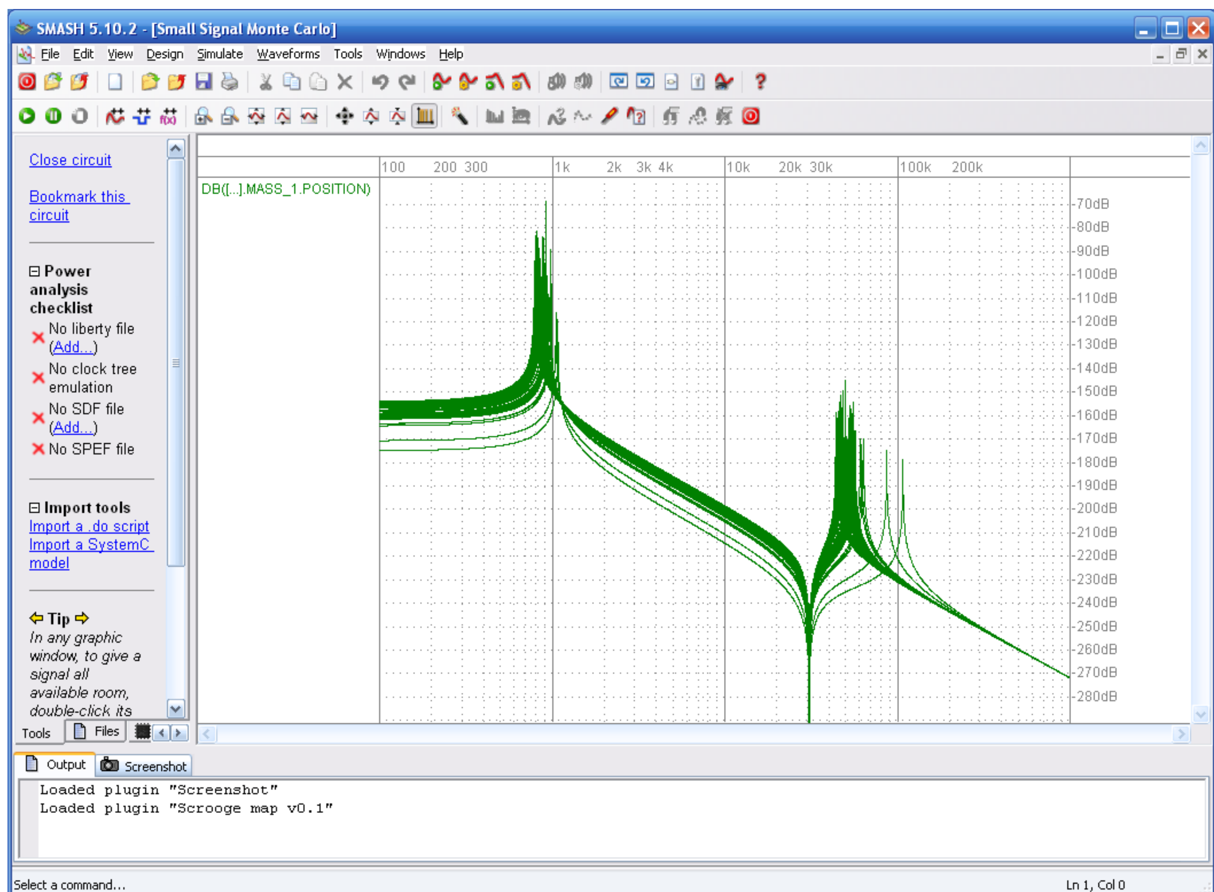

Figure 3: Monte Carlo analysis

4 Conclusion

Applying distribution functions on the parameters of simulation models helps to determine where design or process optimizations become necessary to get the system behavior in an acceptable range. Simulation runs of the optimized design with parameters that match the typical process variations of the production unit allow predicting the yield of the final MEMS devices.

The bundle comprised of the EMBLEM-Mecha basic effects library, the SLED schematic link editor and the SMASH single-kernel mixed-signal multi-language simulator enables the graphic modeling and simulation of such multi-domain systems.

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