Test Support Strategies for MEMS

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Abstract
Integrated test technology is becoming critically important for MEMS due to the high reliability and safety critical applications targeted. High quality levels in production require efficient test strategies that are properly validated. Fault simulation and testability analysis are critical utilities required to support this process.
This paper will discuss methods for achieving test support based on the extension of tools and techniques currently being introduced into the mixed signal ASIC market.

Keywords: MEMS, fault simulation, test support.

1. Introduction

Both current and expected applications of MEMS tend to be in sensing and actuation applications where the device will play a mission critical role. Examples here are pressure sensors for aircraft engine control, vehicle braking, vessel pressure in reactors and medical implants. These devices will also tend to have mechatronic interfaces or at the least, non-electrical inputs and limited access for test. Production test, self-test and on-line data validation will all become critical specifications for these devices.
To achieve fault simulation and testability analysis in these devices, it is necessary to model both the mechatronic and electrical elements within the same simulation environment to ensure the efficient injection and analysis of faults. In most cases, the fault simulation process must be carried out in closed loop configuration to allow non-idealities that can effect fault coverage such as process variations, noise, mode coupling and resolution limitations to be handled correctly.
This paper proposes methods of extending the capabilities of mixed signal and analogue fault simulation techniques to MEMS by including failure mode and effect analysis data and using behavioural modelling techniques compatible with electrical simulators.

2. Previous work

2.1 The FMEA$^+$ concept

FMEA+ was first proposed by Olbrich [1]. The technique relies on integrating top down failure analysis and bottom-up fault simulation. The top-down technique, Failure mode and effect analysis (FMEA) [2], is well accepted by the system design industries whereas fault simulation tends to be restricted to low level components. To illustrate the need for the integration of the two methods, a brief analysis of the types of faults that can occur in MEMS devices reveals the following categories:

- Local defects
- Parameters out of tolerance
- Wear (especially in devices with movable parts)
- Environmental hazards
- Problems due to imperfection in the design process (i.e. design validation poor compared to mixed-signal designs)
- Mode coupling / structure oscillation in incorrect modes
- System level faults (for example crosstalk between signals of different modules)

For CMOS circuits, defect-related and parametric faults are typically taken into account during a fault simulation. FMEA can be used to compile fault lists related to the remaining fault categories. The procedure involves:

1. Identification of all the functions of the system at all levels of hierarchy (component, system block, and system) to be analysed.
2. Anticipation and description of how the parts at the different levels of hierarchy can fail (failure mode).
3. Assumption that failures have occurred and description of effect(s).
4. Identification of every possible fault cause for the failure mode.

In a Failure Mode, Effect and Criticality Analysis (FMECA) [2,3] a ranking system is used to express the severity of the failure mode, its’ chance of occurrence and the likelihood of it being detected. FMECA will simply be denoted as FMEA throughout this paper.
A FMEA is ideally performed by a team of specialists involved in the design of the system. The advantage of performing a FMEA is that all possible causes of faults can be taken into account. Furthermore, since the analysis is performed at different levels of hierarchy,

failure modes can be predicted at an early stage of the design.

However, it will not be possible to predict all failure modes and their effects accurately in a FMEA meeting. Furthermore, the ranking of the different faults is based on the subjective judgement of the FMEA team members. Therefore, it is proposed in [1] to combine the top-down FMEA approach with the bottom-up fault simulation approach, resulting in the FMEA$^+$ methodology.

2.2 Analogue and mixed-signal fault simulation

The methodology generally used to generate the fault list for analogue and mixed fault simulation is shown in figure 2.1. The following procedures are core to the success of the methodology:

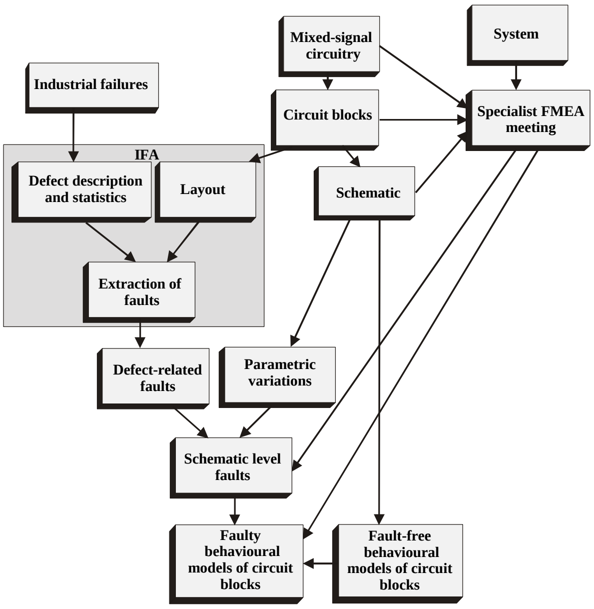

Figure 2.1. Generation of the fault list and behavioural models for mixed-signal circuitry in the FMEA$^+$ approach

1. Inductive Fault Analysis (IFA) [4] [5]. Here a fault list based on the actual defects occurring in the layout can be obtained.
2. Parametric faults involving no change to the netlist due process variations and component value changes that may cause the system to fail its' specifications.
3. The generation of behavioural models of the fault-free and faulty circuit blocks that can be used in a hierarchical fault simulation of the entire system. This will be described in section 2.3.

2.3 Sensor and actuator fault simulation

To generate a fault list, fault-free and faulty behavioural models for a sensor or actuator, a similar procedure as that for mixed-signal circuits is feasible. This is shown in figure 2.2.

The sort of defects that can occur in these kind of structures can be determined from observations of failed devices. In [6] the most typical failure mechanisms in a bulk micromachining process are identified for each technology step together with the faults & deviating parameters caused by those mechanisms. A specific failure category, called stiction is investigated in [7].

In [8] the effect of particulate contaminations is investigated by inserting them into a mesh description of the structure and performing finite element simulations using a Monte Carlo approach. The observed faults can directly be mapped to the faulty behaviour of the entire structure. They can however also be used to describe faults in the different components (such as beams and masses in a mechanical structure), which can be used to build a database of component level faults. This information can be reused for other structures built out of similar components.

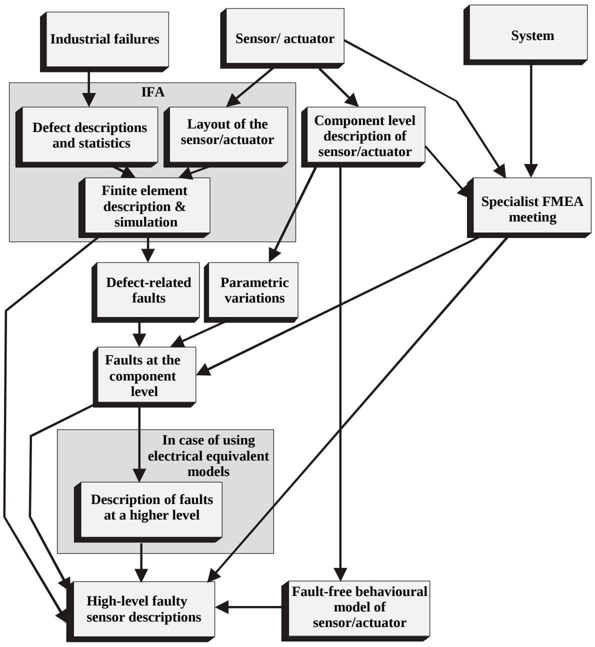

Figure 2.2. Generation of the fault list and behavioural models for sensors/actuators in the FMEA$^+$ approach

In the case where an electrical equivalent model is used as a high-level description of the structure, the component level faults have to be mapped to equivalent faults in the electrical domain. In [9] a HDL-A fault model library is used for this purpose.

The results of the trajectories shown in figure 2.1 and 2.2 can be used to perform a hierarchical and statistical fault simulation on the entire Microsystem. The results of this simulation identify difficult to detect faults and the possible need for DfT or BIST integration. This is shown in figure 2.3.a. In figure 2.3.b, hierarchical simulation of the system block is achieved by describing faults at either the component level or through faulty behavioural models. This system block can be either an electrical circuit block or a sensor/actuator.

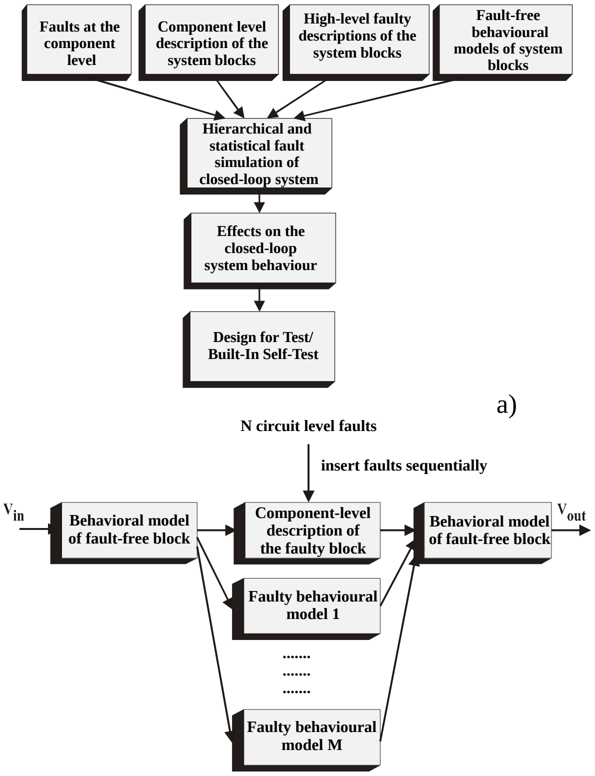

Figure 2.3. Achieving DfT or BIST for Microsystems

3. Achieving test support using FMEA$^+$

3.1 Critical problems

The FMEA method described in section 2.1 is not automated. The analysis can be automated using numerical simulations, expert systems [10] or causal reasoning [11]. In all cases, information compiled from previous analysis of similar circuits is used. This reduces the time to generate a list of failure modes. However, both expert systems and causal reasoning suffer from a subjective evaluation of the effects of the failure modes. Furthermore, the methods that are used to evaluate these effects are not compatible with the numerical method used in fault simulation.

To be able to include failure modes from an FMEA into a hierarchical fault simulation of the Microsystem, the modelling of these faults in a form that can be used by the Microsystem simulator has to be achieved. A comparison between the different modelling approaches of sensors/actuators is made in Table 3.1.

A behavioural level description or a schematic level description of the sensor/actuator can be implemented in an electrical simulator, which either incorporates or can be used in combination with a behavioural language supporting the use of non-electrical variables. This enables the combined simulation of electrical circuitry and the sensor/actuator and therefore microsystem fault simulation. Examples of programs that enable these simulations are the combination of ELDO and VHDL-AMS, Saber with its' behavioural language MAST and SMASH with its' behavioural language ABCD [12]. Examples of tools that support hierarchical fault simulation are MiST PROFIT [13], Faultmaxx [14] and GDSFaultsim [15]. Some of these tools combine hierarchical and statistical fault simulation.

The description of sensors and actuators at a component level uses the fact that these structures can be described as an interconnected set of elements. A MicroElectroMechanical Structure can for example be described being built up out of elements such as masses and beams. When behavioural descriptions are generated for those elements, the structure can be modelled at a schematic level. This is similar to an electrical schematic, which consists of a number of electrical components, for which behavioural descriptions (for example the equations modelling a transistor) are derived.

In [16] a nodal simulator, which links descriptions of MEMS components together, is described. Every beam of the design is described as one element characterised by its' stiffness matrix and an effective mass matrix. The simulator can therefore be regarded as a finite element simulator in which every component is modelled by just one element.

	Finite element simulations	Electrical equivalent circuits	Behavioural level description	Schematic level description
Accuracy	++	- (linearisation)	+/-	+
Ability to model unwanted modes	++	-	+/-	+
Speed	-	++	++	+/-
Mixed simulation of electrical circuit and sensor /actuator	-	+	+	+
Extra work for sensor/actuator designer	minimal	much	some	minimal
Skill level of the system designer	high	low	low	low
Ability to model non-electrical signals	++	-	+	+
Suitability for system-level fault simulation	-	+/-	+	++

Table 3.1. Modelling methods for sensors and actuators

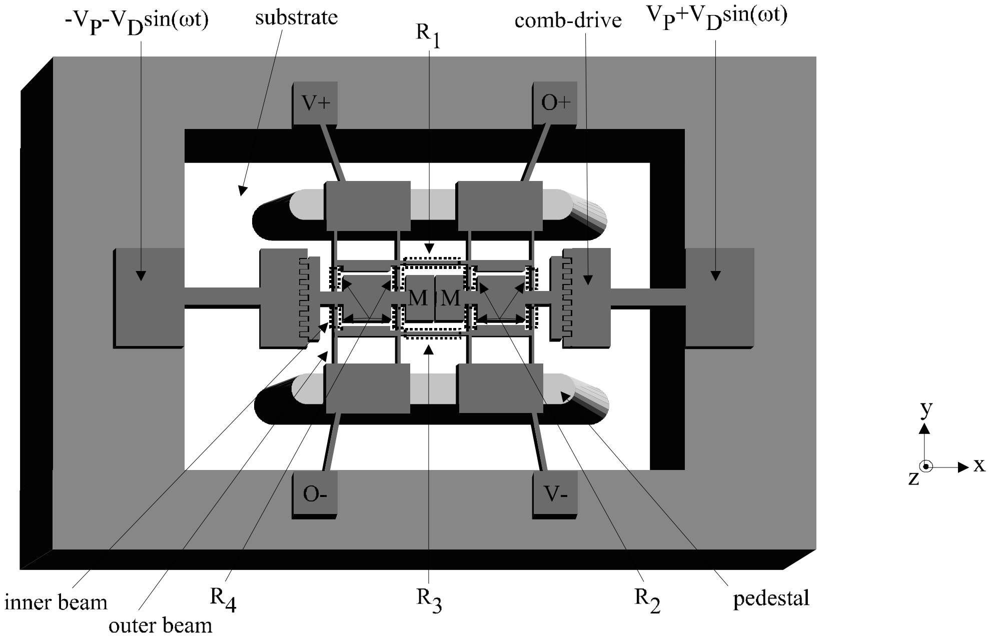

Figure 2.4. Pressure sensor

Modelling of beam elements is described in [17]. The natural frequencies of the beams are simulated by splitting the beam into more than one element. In [18] a microgyroscope system is modelled. Finite element simulations are used to derive descriptions of components for which it is difficult to find an analytical solution.

In figure 2.3 it is shown that both the component level description and the behavioural description of a sensor/actuator are required in a hierarchical fault simulation. A further explanation for the need to use both approaches is given in section 3.2 using an example system.

3.2 Lumped modelling

In figure 2.4 a sketch of an industrial micromachined resonant pressure sensor is shown.
In the operation mode of the system, the electrostatic forces operating in the comb-drives cause the two movable structures to oscillate in opposite directions. The structures therefore separate and then close. Due to the stiffness of the piezoresistors connecting the two movable parts, the movement of the outer beams is negligible compared to the movement of the inner beams. An exaggerated drawing of the movement of the sensor is shown in figure 2.5.

A glass cover over the sensor (not shown) maintains an approximate vacuum, which minimises the viscous drag and therefore maximises the Q-factor of the system. The pressure difference between the upper side of the substrate, exposed to the low pressure in the cover, and the bottom of the substrate (forming part of the bottom of the chip), exposed to the measurement pressure, causes the substrate to bend. Therefore the pedestals move apart and cause a tension in the beams that form the spring. This tension causes the spring stiffness and therefore the resonance frequency of the system to change.

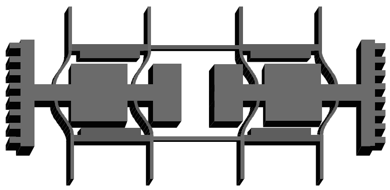

Figure 2.5. Movement of the sensor

A high-level description of this sensor is generated in the behavioural language ABCD within the simulator "SMASH". The movable part of the structure is simply described by its’ mass. The four beams connected to each movable part are modelled as one spring. An analytical solution is used to model the relationship between the stiffness of the beams (spring ‘constant’) and the tension in the structure. An equivalent mass of the beams is calculated and added to the mass of the movable part.
The bending of the substrate and therefore the relationship between the measurement pressure and the tension in the springs is currently under investigation.
An analytical solution is used to model the relationship between the applied drive voltage and the electrostatic force. The electrical behaviour of the comb-drive has been modelled as a varying capacitance under influence of movement.
The piezoresistors R4 and R2 (both consisting of four resistors) will not change value during movement, since the effect of part of each resistor being compressed is cancelled out by the other part being extended. The piezoresistors R1 and R3 change value with a frequency equal to the resonance frequency of the structure. The applied force to and the relative change of resistance value of these piezoresistors are related by the piezoresistance coefficient, π. From

figure 2.4 it can be seen that the piezoresistors form a Wheatstone bridge, as is schematically modelled in figure 2.6.b. The output (O+ - O-) of this bridge is the sum of a sine wave voltage at the resonance frequency and a bias voltage.

In [19] damping in laterally driven microresonators is derived based on Stokes flow and Couette flow. Analytical solutions are found to match experimental results for resonators operating at atmospheric pressure. For systems operating at very low pressures, the viscosity of the ambient gas is not well defined and it becomes more difficult to derive damping. Furthermore, damping mechanisms in the material might not be negligible anymore. Further research has to be applied in this field.

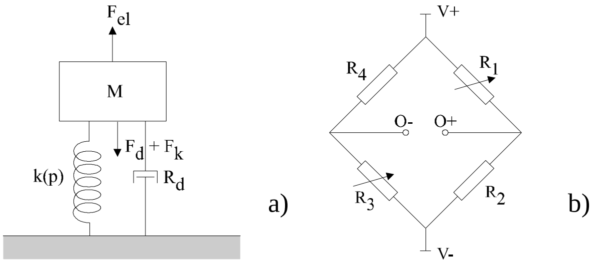

Figure 2.6. Behavioural modelling of the sensor

The sensor is implemented as a set of equations in a subcircuit of a system netlist. The differential equation describing the mass-spring damper system shown in figure 2.6.a (and therefore the movement of one side of the structure) is for example implemented in the following way:

```
 make_equal(S(XDERIV),S'(X));
make_equal((MEFF*S'(XDERIV) +
C*S(XDERIV) + K*S(X)), S(F));
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S( ) indicates that a state variable is being used. F is the sum of forces operating on the mass. The following equation is therefore implemented:

$$M_{eff} \cdot \ddot{x} + c \cdot \dot{x} + k \cdot x = F$$

where M_{eff} denotes the effective mass, x denotes the displacement in the x direction, c denotes the damping and k denotes the spring ‘constant’ (which is dependent on the force that the pedestals exercise on the beams and therefore derived in a previous equation).

Behavioural models of the electrical circuit blocks of the system have been generated. These will be included to enable a nominal hierarchical simulation of the entire system.

3.3 Fault modelling

As was explained previously, to enable a hierarchical fault simulation, faults in the sensor have to be modelled in a form compatible with the fault simulator. Faults that influence the behaviour of the entire sensor have to be modelled at the behavioural level. By adapting the equations in the nominal behavioural model, a faulty behavioural model can be generated.

Other faults have to be modelled at the component level. Assume for example that a fault in one of the four beams connected to a movable structure causes the stiffness of this beam to change. Due to the resulting asymmetry in the force-distribution, the structure will not only translate, but also rotate. This effect can not be modelled at the behavioural level, since the distributed nature of the spring is not taken into account at this level.

When a component level description is used, and every component is described as a parameterised cell, both defect-related faults and parametric faults can be described at the component level, by adapting the behavioural description of the component. This has the advantage that a library of component level fault models can be generated and reused in other designs. Furthermore, the likelihood of occurrence of each fault can be predicted from the dimensions of the structure the fault is located in.

The previously described model can be adapted to generate a component level model. This level of simulation is possible using SMASH.

To enable modelling of FMEA failure modes, it is necessary to categorise these failures to the level of modelling they require. The following categorisation is proposed:

- Failures that are directly linked to certain components.
- Failures that can't be automatically linked to a single component and therefore have to be described at a system level.

The effects of system level faults have to be investigated. The other causes of failure mentioned in section 2.1 can be categorised.

The first category of faults contains some environmental effects and all other faults mentioned in section 2.1. The effect of extreme temperatures on the sensor operation can, for example be taken into account by modelling the relationship between temperature and the material properties of each component. Wear will also change the material properties of some components.

By describing the relationship between the failures in the first group and their effects at the component level, fault libraries can be constructed for each component containing those failure modes. For each basic component of a sensor, these libraries only have to be derived once. They can be re-used in the design of other sensors and therefore reduce the time needed to generate the fault list.

Some environmental effects influence the operation of the sensor as a whole. If the pressure sensor is for example exposed to vibrations, additional forces will be generated on the movable parts. These forces are not directly linked to one of the components. This type of error is therefore difficult to build into component level fault models. They are found by reasoning at a system level and can be modelled at the sensor level. This type of fault belongs in the second category. Part of these faults can be predicted from experience with failures of similar devices.

4. Conclusions & future work

To enable investigation of the effects of all possible sources of faults, FMEA$^+$, a combination of Failure Mode and Effect Analysis (FMEA) and fault simulation, has to be used. It is shown how both approaches can be combined. Furthermore, automation of the extraction of FMEA failures is proposed by way of categorisation of these failures and use of fault libraries. An FMEA$^+$ analysis on a pressure sensing system is initialised by behavioural modelling of the different components of the sensor.

Further research will include a deeper investigation into the categorisation of different failures and the modelling of these failures. Furthermore, the behavioural description and component level description of the pressure sensor will be generated.

Application of the described strategies will lead to DfT and/or BIST proposals for this and other types of similar systems.

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