# A New Method for the Analysis of Movement Dependent Parasitics in Full Custom Designed MEMS Sensors

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***Abstract*—Due to the lack of sophisticated microelectromechanical systems (MEMS) component libraries, highly optimized MEMS sensors are currently designed using a polygon driven design flow. The strength of this design flow is the accurate mechanical simulation of the polygons by finite element (FE) modal analysis. The result of the FE-modal analysis is included in the system model together with the data of the (mechanical) static electrostatic analysis. However, the system model lacks the dynamic parasitic electrostatic effects, arising from the electric coupling between the wiring and the moving structures. In order to include these effects in the system model, we present a method which enables the quasi dynamic parasitic extraction with respect to in-plane movements of the sensor structures. The method is embedded in the polygon driven MEMS design flow using standard EDA tools. In order to take the influences of the fabrication process into account, such as etching process variations, the method combines the FE-modal analysis and the fabrication process simulation data. This enables the analysis of dynamic changing electrostatic parasitic effects with respect to movements of the mechanical structures. Additionally, the result can be included into the system model allowing the simulation of positive feedback of the electrostatic parasitic effects to the mechanical structures.**

## I. Introduction

Over the past few years, the development of a component library driven design flow for microelectromechanical systems (MEMS) has come into the focus of researchers (e.g. [1]–[3]). The tools of this design flow are well integrated in the common integrated circuit (IC) design environments (e.g. Coventor [5], IntelliSense [6]). Most of these tools also provide the extraction of a multi physics system model for the co-simulation and -optimization with the evaluation circuit. Overall, the component library driven design flow enables small and fabless companies to develop low volume MEMS devices.

The drawback of these pre-designed components is that they limit the design freedom. Therefore small and highly sophisticated MEMS are currently designed in a polygon driven design flow. The strength of this design flow is the highly accurate mechanical simulation of the polygons by finite element (FE) analysis.

A common FE tool like ANSYS [7] can run a multi physics analysis on a meshed 3D-model in an acceptable time if the MEMS device has an adequate simple structure [4]. For actual sophisticated MEMS devices, the multi physics 3D simulation takes too much time so it can not be integrated into an efficient design flow. Therefore, the mechanical analysis is done by a much faster FE-modal analysis on an Timoshenko beam model of the MEMS device. Aside from precise mechanical analysis, this approach only accounts for the *static* electrostatic influences, i.e. coupling capacitances of structures which are considered to be stationary. All additional electrostatic effects, in particular changing parasitic coupling capacitances arising from movements/deflections of the MEMS structures are neglected. These kinds of effects we call *dynamic* electrostatic effects.

To close this gap, we present a method which approximates the dynamic electrostatic behaviour of the MEMS device by a quasi static analysis. The goal of our approach is to analyse the dynamic of the coupling capacitance in a sequence of deflection phases. Therefore, for each deflection phase a electrostatic analysis is performed. The electrostatic analysis combines the data of the FE-modal analysis with the fabrication process simulation (e.g. influences of the etching processes). The models of the quasi static analysis can be handled by a commercial electrostatic analysis tool. In the end, the results of the sequence of electrostatic analyses can be interpolated. The result is an approximation of the dynamic electrostatic behaviour.

With this, it is possible to integrate the dynamic electrostatic behaviour along with the mechanical behaviour into the design flow. For example, this enables the simulation of noise effects triggered by dynamic parasitic coupling capacitances and their positive feedback to the mechanical behaviour of the MEMS device.

The problem is described in detail in Section II. Section III shows the modelling of the dynamic electrostatic behaviour. In Section IV the method is demonstrated on a MEMS sensor. The paper closes with a summary and a look at further works in Section V.

## II. Problem description

Most MEMS devices are fabricated in silicon. Commonly, they are composed of movable mechanical elements and wires. A particular feature of MEMS is that the wiring can also be

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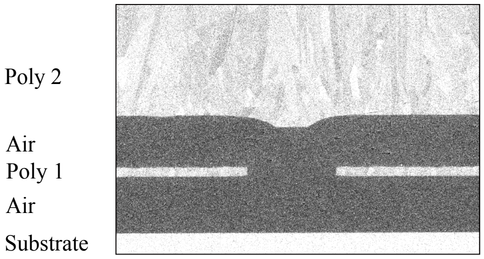



**Fig. 1:** REM picture of a cross section of a MEMS structure. The center of the picture shows the topography at the bottom side of the second layer (poly 2). This topography is caused by the structuring of the first layer (poly 1) during the fabrication process.

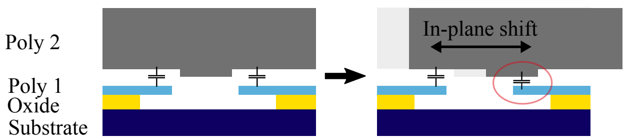



**Fig. 2:** Schematic cross section of a MEMS sensor structure. Poly 1 (blue): wires, Poly 2 (grey): mechanical structure. Left: The movable structure is in resting position. The coupling parasitic capacitances are symmetrical. Right: The movable structure is shifted. The parasitic coupling capacitance on the right side increases whereas the one on the left side stays constant.

under the movable elements. This results in parasitic coupling capacitances between the wires and the mechanical elements. Additionally, wires under movable structures can result in dynamic parasitics when the structures are moving. Especially in MEMS sensors, these parasitic coupling capacitances can cause crosstalk between signals or positive feedback converted into a mechanical deflection.

In the following, we will refine the problem for capacitive inertial MEMS sensors. Similar effects can be observed on commonly used MEMS devices.

Conventional inertial sensors have the following structure and working principle. They are composed of a movable seismic mass which is connected by springs to anchor points. The electrode structures are located close to the seismic mass. The electrodes have two different electrical potentials. Hence, there are coupling capacitances between the seismic mass and the electrodes. Thus, moving the seismic mass causes a changing in the coupling capacitance. The change of the coupling capacitances is evaluated by a customized circuit.

During the fabrication of the MEMS sensor, topography steps can arise, as shown in Fig. 1. If the sensor is deflected such topography steps could move over wires. This would result in a change of the coupling capacitance (Fig. 2). This, in turn, disturbes the output signal due to the capacitance measurement principle of the inertial MEMS sensors.

The analysis of the dynamic electrostatic behaviour enables the analysis of the dynamic parasitic coupling capacitances during the design phase and will avoid expensive redesigns and reduce the time-to-market.

Often, inertial MEMS sensors measure an acceleration or

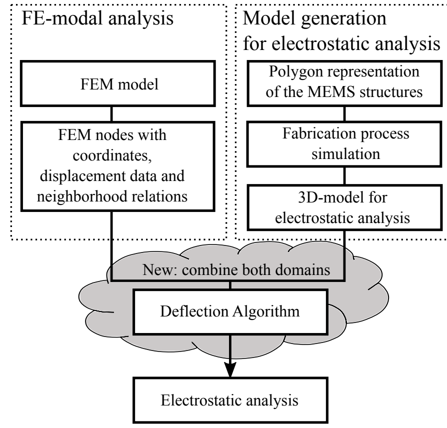



**Fig. 3:** Our approach for the quasi electrostatic analysis flow: combining the mechanical FE-modal analysis with the electrostatic model.

rotation by an out-of-plane deflection of the seismic mass. As shown in Fig. 2, the major part of the dynamic changing parasitic effects are caused by in-plane movements of the seismic mass. Out-of-plane deflections can only amplify such effects. Therefore, only in-plane movements are considered in the following.

## III. Modelling of the Dynamic Electrostatic Behaviour

The modelling of the dynamic electrostatic behaviour is done by a sequence of electrostatic analyses. Each quasi electrostatic analysis represents one deflection state of the MEMS device.

In the following subsections, the quasi electrostatic analysis is described in detail. Figure 3 gives an overview of the flow.

### A. *Finite Element Modal Analysis*

During the design of the mechanical elements, the mechanical behaviour is simulated by a FE-modal analysis on an Timoshenko beam model. The nodes of the FE model are the start and end points of the Timoshenko beams and can be exported with their coordinates, displacement information and neighbourhood relations.

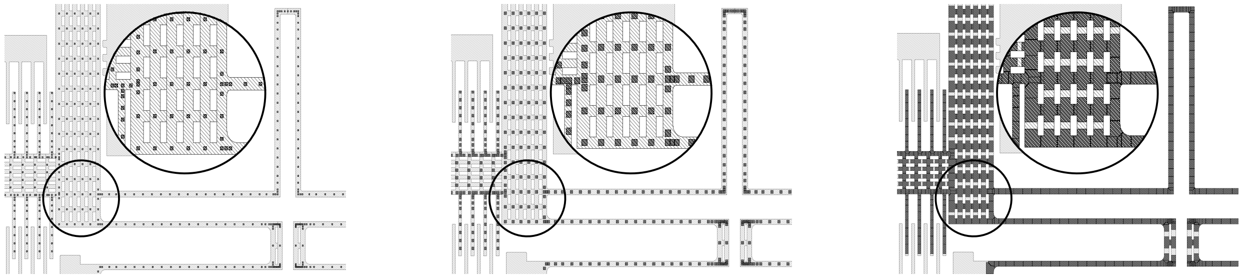
### B. *Model generation for electrostatic analysis*

The physical design includes among others the wiring of the mechanical elements. The result is a polygon representation of the whole MEMS device.

The fabrication process simulation calculates a simplified 3D-model from the polygon representation for the electrostatic analysis. This model includes the influences of the etching processes and topography steps (see Fig. 1).

### C. *Deflection Algorithm*

The deflection algorithm combines the exported node data of the FE-modal analysis with the model of the fabrication process simulation. The combination is done by mapping each node to a unique part of the geometry of the fabrication process simulation model. Afterwards, the displacement information of



**(a)** Growth after 10 iterations **(b)** Growth after 20 iterations **(c)** Growth after 80 iterations

**Fig. 4:** Growth of the initial rectangles until they overlay the whole geometry.

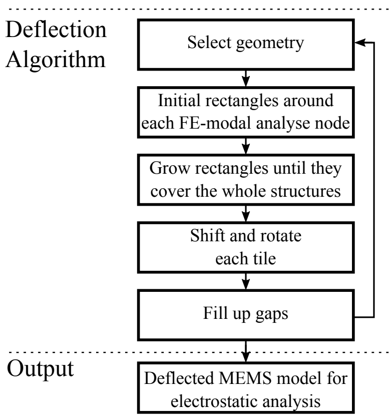



**Fig. 5:** The deflection algorithm flow.

the nodes is used to shift the related parts of the geometry. The result is a first order approximation of the deflected MEMS structures. Figure 5 shows the steps of the deflection algorithm which are described in detail in the following.

The algorithm selects from the model of the process simulation the geometry of the layer which shall be deflected. The mapping of the nodes to the geometry is done by generating a very small initial rectangle around each node. All nodes, which are not inside the selected geometry are neglected. A commercial layout verification tool calculates the growth of all regular rectangles inside the current geometry. The initial rectangles are repeatedly grown until they overlay the whole selected geometry (Fig. 4).

Now the selected geometry is segmented into small tiles and each node of the FE-modal analysis is mapped to one of these tiles. Each tile inherits from its node the displacement information from the FE-modal analysis so each tile can be shifted by this displacement information (Fig. 6). The result is a coarse block representation of the selected geometry of the deflected MEMS (Fig. 6). We refine this first order approximation by applying an additional rotation to each tile. The rotation angle of each tile is derived from the associated geometry. The loop ends with the filling of all small gaps between the tiles.

Finally, the algorithm returns a deflected MEMS model for the electrostatic analysis. Figure 7a shows a part of such a model. For comparison, Fig. 7b shows a microscopic picture of the same MEMS structure. Please note, due to our approach,

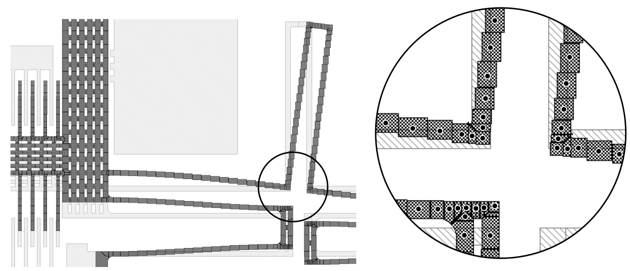
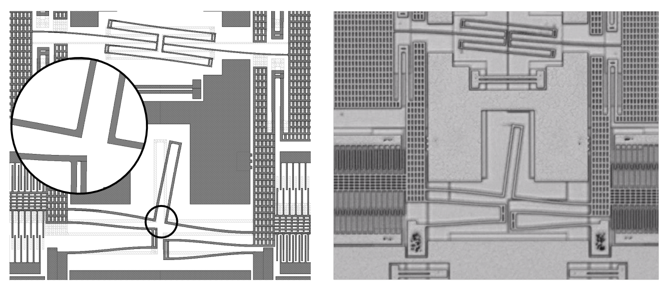


**Fig. 6:** Shifted tiles by FE-modal analysis displacement data.



**(a)** The final deflected model for the electrostatic analysis.

**(b)** Microscopic picture of the same deflected structure.

**Fig. 7:** The final deflected model for the electrostatic analysis compared to a microscopic picture of the deflected structure.

that the deflected MEMS model for the electrostatic analysis still includes the properties of the original fabrication process simulation like the topography steps.

### D. Electrostatic Analysis

The electrostatic analysis is done by a commercial field-solver. It extracts a detailed net list and the coupling capacitances between all nets of the MEMS device which are defined by the bond pads.

The result of the quasi electrostatic analyses is a sequence of data points. These data points represent the mapping between the deflection of the MEMS structure and the associated coupling capacitances. This enables the designation of dynamic parasitic coupling capacitances in respect to movements of the mechanical structures.

To get a continuous mapping from the deflection to the coupling capacitances, the data points can be interpolated. The continuous mapping can be integrated in the system model. This enables the analysis of the influences of the

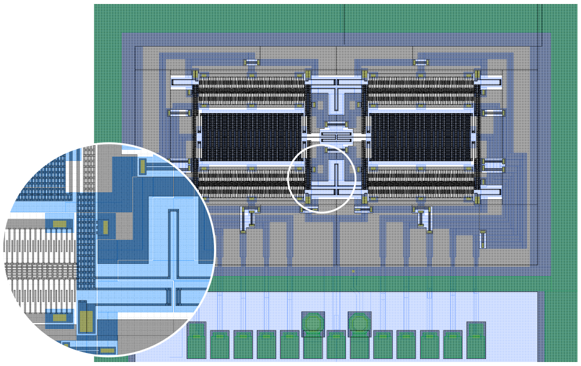


**Fig. 8:** Simple yaw rate sensor which is used for the demonstration.

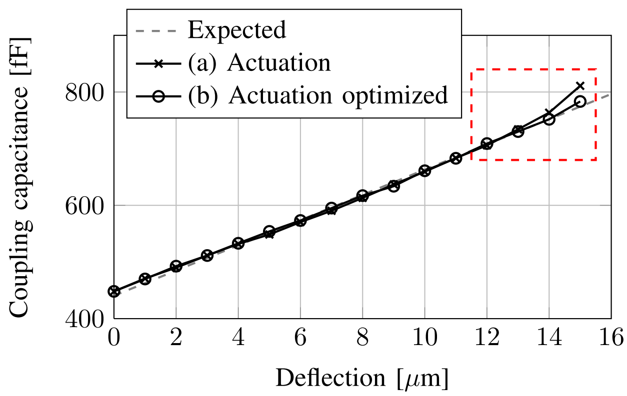



**Fig. 9:** Change of the coupling capacitances between the seismic mass and the drive combs in relation to the deflection: (a) before and (b) after optimization of the geometry.

dynamic parasitic coupling capacitances on the behaviour of the whole system (e.g. noise, positive feedback to the mechanical structure or interference between signals).

## IV. Demonstration

We demonstrate our method on a simple yaw rate sensor shown in Fig. 8. For the dynamic analyses, the deflection range is selected from 0 to 15 $\mu$m. For this purpose sixteen electrostatic analyses, one every micron, are executed. For the demonstration, only the dynamic coupling capacitance between the actuation net and the seismic mass is plotted in Fig. 9.

Due to the interlaced comb structures moving into each other, a linear increase of the coupling capacitance is expected. But as can be seen in Fig. 9, the curve (a) is only linear in the deflection range from 0 to 12 $\mu$m. The non-linearity is caused by the head ends of the comb fingers. They form plate capacitors with the opposite structures. After enlarging the gaps between the head ends and the opposite structures, the coupling capacitance increases linearly over nearly the whole deflection range as shown in Fig. 9, curve (b).

Figure 10 shows in detail the deviation of the extracted values to the expected.

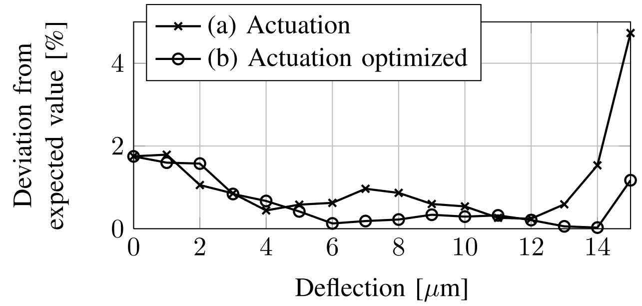



**Fig. 10:** Deviation of the extracted values from the expected.

## V. Summary and Outlook

With the presented method, it is possible to include the analysis of dynamic parasitic coupling capacitances with respect to the movements of the mechanical structures into the polygon driven MEMS design flow. Furthermore, the results can be included into the system model. This allows the simulation of the influences of the dynamic electrostatic parasitic effects on the whole system (e.g. positive feedback of the parasitic coupling capacitances to the mechanical structures).

We presented the method using a MEMS yaw rate sensor, but in general the method is adaptable to every MEMS device for which the needed FE-modal analysis and fabrication process simulation data are available.

For a more detailed analysis, further work will use a combination of the current dynamic analysis method with the detailed circuit extraction algorithm of our previous work [8].

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