Multiphysics System Simulation for MEMS Inertial Sensors

Robert Sattler
University of Applied Sciences Regensburg

Seybothstr. 2, 93053 Regensburg, robert.sattler@hs-regensburg.de

Abstract: This paper gives an overview of modelling microsensors on geometry and system level. The focus will be on the generation of the multiphysics reduced order system model and the coupling with package and ASIC models. The method is based on modal superposition. This means all the details of the sensor can be considered in a finite element model. The mechanical mode shapes of this model form the basis of the reduced order model that can be coupled with other physics or models.

Other physics can be fluidic damping or electrostatics for the drive and sense electrodes. Other models can be a package model to account for offset, a shift in sensitivity with temperature or the excitation of parasitic modes due to vibration. A possible application of the methodology is a gyro design which is more robust to vibrations.

Keywords: multiphysics, reduced order model, system simulation, inertial sensor

1. Introduction

Inertial MEMS sensors like gyros are well established in the automotive industry. Yaw rate sensors can be found in more and more cars, but even higher volumes are expected for consumer applications like navigation, image stabilization or gaming.

To be competitive in the consumer market, cost and time to market have to be reduced. This means costly redesigns of sensor hardware samples have to be avoided and replaced by modelling.

Sensor design and principle

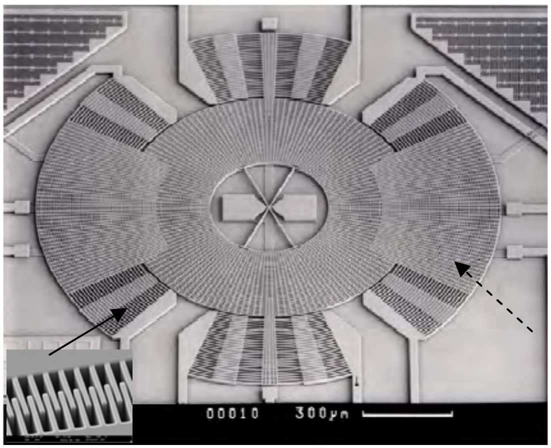

Figure 1: Scanning electron microscope image of a gyroscope.

The yaw rate is detected by the Coriolis force acting on moving bodies in a rotating system. Therefore the sensor must be permanently in motion to sense the coriolis force. This resonant harmonic drive motion is typically realized by electrostatic combdrives (indicated by the solid arrow in figure 1). An external yaw rate results in a coriolis force which deflects the detection electrodes (indicated by the dashed arrow in figure 1). The deflection electrodes operate like a parallel plate capacitor. A reduced gap means a higher capacitance or voltage signal.

2 Sensor Modeling

Such complex sensor designs require on the one hand very detailed FE-models. On the other hand the inherent dynamics of the sensor operation require transient simulations, which can not be performed in reasonable time detailed FE-models.

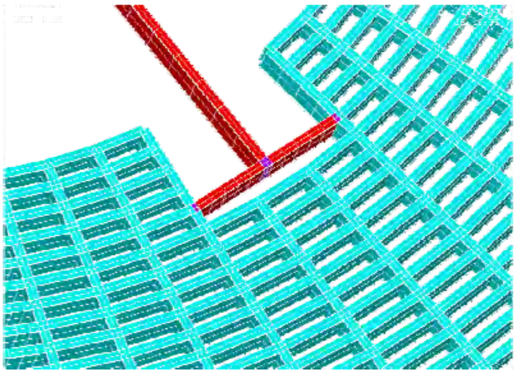

Figure 2: Detailed view on finite element model of a gyroscope

A methodology that accounts for both contrary demands is reduced order modelling (ROM) based on modal superposition [1, 2].

2.1 Reduced order model

The FE-equation of motion

$$M\,\ddot{x} + D\,\dot{x} + K\,x = F$$

is a second order differential equation with typically about 100.000 degrees of freedom **x. M**, **D**, **K** represent the mass-, the damping- and the stiffness matrix, **F** the vector of forces.
The FE degrees of freedom **x** are transformed to a few modal degrees of freedom **q**:

$$x = \phi q$$

The transformation matrix Φ consists of eigenvectors from the modal analysis of structural mechanics. The system matrices and the forces are transformed according to

$$\begin{aligned}\tilde{M} &= \phi^t M\,\phi\\ \tilde{D} &= \phi^t D\,\phi\\ \tilde{K} &= \phi^t K\,\phi\\ \tilde{F} &= \phi^t F\end{aligned}$$

About a dozen eigenmodes are sufficient to approximate the system behaviour. So the reduced equations of motion

$$\tilde{M}\ddot{x} + \tilde{D}\dot{x} + \tilde{K}x = \tilde{F}$$

is a decoupled set of second order differential equations which can be modeled very efficiently in Matlab/Simulink.

2.2 Multiphysics

So far only the linear equations of motion are modeled, but other physics can easily be implemented into the model, because the transformation matrix allows easy and fast switching between modal (ROM) and nodal (FEM) coordinates during the simulation.

Electrostatics: combdrives and detection electrodes can be included by analytical equations or fit functions to account for fringing fields in the comb drives and the perforated detection electrodes.

Mechanics: external accelerations like vibrations, coriolis forces and contact forces can be implemented with analytic expressions.
Quadrature is a parasitic effect due to inevitable process inhomogeneities, which can be extracted from the finite element model. In the reduced order model it is represented by off-diagonal elements in the stiffness matrix **K**.
Nonlinear effects in springs can also be extracted from nonlinear finite element analysis and implemented in the reduced order model by an additional force term that is varying with amplitude.

Fluidics: Squeeze-film damping is the dominant damping effect in microsystems. Due to the small gaps the air can be trapped and behave not only as a damper, but also as a spring. This frequency dependend effect can also be extracted from the finite element model by solving the Reynolds equation for each relevant mode with a harmonic analysis. The complex damping coefficient can be considered in the reduced order model.

Magnetics: Lorentz forces (typically not used for inertial sensors but widely used for micro actuators) can be implemented by analytical expressions or fit functions from finite element simulations.

3 System modeling

The sensor model itself can deliver the basic facts for the sensor data sheet, like resonance frequency, sensitivity or yield due to process variations. But cross-coupling effects between package, sensor and ASIC cannot be considered. But these parasitic effects become more and more important. As there is an increasing competition on the sensor market, there is a trend using standard ASICs and packages to profit from economy of scale. But the result is an increase in parasitic cross-coupling.

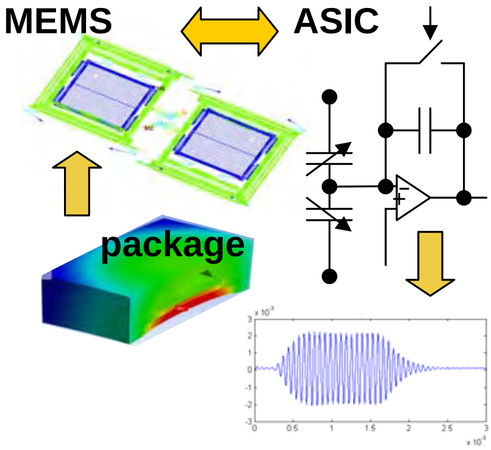

Figure 3: System model of a gyroscope

3.1 Package (static)

To get high quality resonant driving amplitudes the sensor has to be packaged in vaccum. At various temperatures materials with different coefficients of thermal expansion are glued or molded. This results in a temperature dependent warpage of the package as depicted in figure 4.
One consequence is a shift in the suspension points of the sensor indicated by four dots in the center of figure 4. Stress and a temperature dependent shift in the resonant frequencies of the sensor are possible implications. This temperature dependency can be accounted for by parametric reduced order modelling [4].

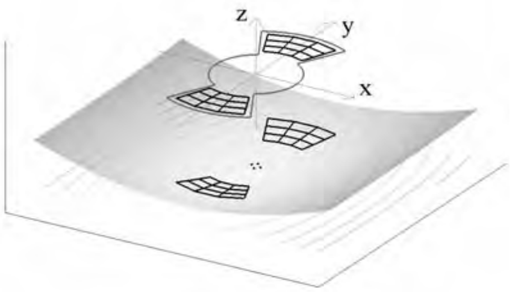

Figure 4: Sensor over curved substrate

Another consequence ist the influence on the electrostatics. Both for the combdrives and the detection electrodes, the capacitance and the electrostatic forces strongly depend on the distance to the substrate. So a warped substrate results in a temperature dependent driving and detection signal due to a change in capacitance.

Comb drives do not only supply inplane forces, but also levitation forces due to fringing electrostatic fields. As comb drives are located symmetrically on the sensor, levitation forces should not tilt the sensor. Substrate warpage can change this situation. Different levitation forces on opposite sides of the sensor will tilt the sensor in the same way as the coriolis force would do. This means the sensor has an package induced offset.
Taking into account both effects in the reduced order model allows to calculate the temperature dependent offset and sensitivity of the sensor as shown in figure 5.

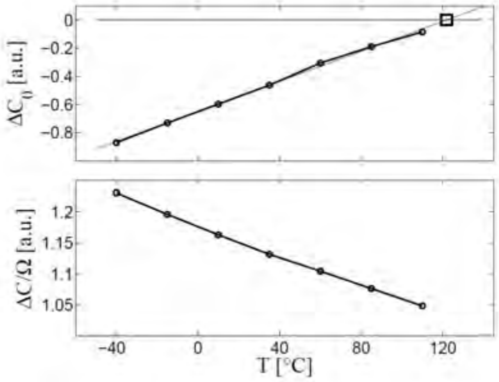

Figure 5: Sensor offset and sensitivity vs. temperature

More details on the reduced order model package simulation and results in comparison with measurements can be found in [3].

3.2 Package (dynamic)

The package can not only statically be deformed, but also dynamically. According to the shape of the package certain resonant modes can be excited. This stimulation can be initiated from outside (e.g. the sensor is mounted close to the engine) or from the sensor inside. A digital ASIC is using a high frequency clock pulse for the driving voltage and the feedback voltage. This could excite a package mode and influence the sensor in a parasitic way.
To account for these effects reduced order models of the sensor and the package have to be generated and coupled by mechanical springs representing the suspension of the sensor in the package. In this case the modal analysis of the

sensor (to extract the eigenvectors for the transformation matrix) must be performed without mechanical boundary conditions at the suspension nodes.

3.3 ASIC

The ASIC does not only evaluate and filter the sensor signals, but also give active feedback by bringing the drive mode into resonance and keeping the sense mode stable by balancing feedback forces on the detection electrodes.

The easiest approach to integrate the ASIC into the simulink system model is a behavior model of the ASIC in simulink. But this approach allows only a rough approximation of the real ASIC.

Alternatively the system model of sensor and package can be exported as C-Code and integrated in a dedicated digital ASIC-simulation tool as ModelSim or Cadence. However this approach is computationally very intensive.

For complex ASIC models the best approach is to export the ASIC model to an FPGA that has a PCI-interface to simulink. The ASIC is running in real time on the FPGA, so the only bottleneck for the coupled simulation is the PCI interface.

4. Conclusions

Simulation and modeling becomes more and more relevant for the development of new sensors. Apart from finite element modeling on geometry level, modeling on system level is indispensable. The former allows high accuracy as based on exact physical equations; the latter is based on simplified models, but allows transient simulations to take dynamic effects into account. The method reduced order modeling allows benefiting from the advantage of both levels of abstraction. The present paper describes the method of modal superposition to generate the reduced order models. This reduced order model is not a black box and therefore very flexible.

On the one side one can integrate other physics and nonlinear effects or even couple other models like package models. On the other side one can switch in the model between modal and nodal coordinates: Damping does affect all nodes so this effect is described in modal coordinates. Electrostatic forces or contact forces will only affect view nodes of the total model, so these effects are most efficiently modeled in nodal coordinates and then transferred to modal coordinates by the transformation matrix.

Nevertheless the model is still very detailed as based on all nodes of the FE-model. So process inhomogeneities affecting single springs like quadrature can also be considered in the reduced order model.

This allows for the first time to build a detailed model of a complete sensor including sensor, package and ASIC. This model can help to understand the interaction between the three components. As these are typically developed independently from different teams, there is no overlapping expertise. So this model can help to gather experts from sensor design, ASIC design and package design and discuss the results from the simulation. Hence sensor, package and ASIC are not optimized individually and locally any more, but holistically and globally. This allows a fast development of robust sensors with sufficient yield in mass production.

5. References

1. D. Gugel, Ordnungsreduktion in der Mikrosystemtechnik, der Andere Verlag, Chemnitz Technische Univ., Diss., (2009)

2. L. Gabbay, J. Mehner, S. Senturia, Computer-Aided Generation of Nonlinear Reduced-Order Dynamic Macromodels-I: Non stressed stiffened case, J. of Microelectromechanical Systems, 9, No. 2 (2000), S. 262-269.

3. D. Gugel, R. Sattler, J. Mehner , W. Dötzel, Ordnungsreduktion als Simulationsmethode zur Berücksichtigung von Einflüssen der Aufbau- und Verbindungstechnik in der MEMS Gesamt-systemsimulation, MikroSystemTechnik KONGRESS 2007, Dresden.

4. D. Gugel, W. Dötzel, Parametric Reduced Order Modeling for Industrial MEMS Design Processes, Proceedings of Smart System Integration, Paris, France, 2007.