Model Building, Control Design and practical Implementation of a high precision and high dynamical Acceleration Sensor

Wolfram, Heiko[a]; Schmiedel, Ralf[b]; Kurth, Steffen[c]; Mehner, Jan[c]; Hiller, Karla[b,e]; Aurich, Torsten[d]; Günther, Wolfgang[d]; Dötzel, Wolfram[a]; Geßner, Thomas[e,b,c]

[a]Chemnitz University of Technology, Faculty of Electrical Engineering and Information Technology, Department of Microsystems and Devices,

[b]Chemnitz University of Technology, Faculty of Electrical Engineering and Information Technology, Center for Microtechnologies,

[c]Fraunhofer Institute for Reliability and Microintegration,

[d]GEMAC - Gesellschaft für Mikroelektronikanwendungen Chemnitz m.b.H.,

[e]Chemnitz University of Technology, Faculty of Electrical Engineering and Information Technology, Chair of Microtechnology.

Abstract

This project deals with the development of an acceleration sensor system. The starting point is a theoretical model, built from the physical principles of the complete sensor system, consisting of the MEMS (*Micro-Electro-Mechanical Systems*) sensor, the charge amplifier and the PWM (*Pulse-Width Modulation*) driver. The LTI (*Linear Time-Invariant*) system, derived at the operating point, is used to design a robust control with the *Mixed-Sensitivity H-infinity Approach*. The system contains an unstable pole and unstable zeros, resulting from the electrostatic spring softening and time delay, imposed by the A/D-D/A conversation delay and DSP computing time. Thus, limitations for the control design are given. Parameters of the real system, which are needed for the theoretical model description, are either inaccurate, because of tolerances in every sample. Or they are just unknown. Therefore, the theoretical model lacks of completeness or might be inaccurate. A new two-stage identification scheme is deployed to the system to overcome the instability and to obtain the parameters directly from the "real world". The first samples have archived a resolution of better than 500 μg and a closed-loop bandwidth of more than 200 Hz.

1 Introduction

MEMS play an important role in the realization of sensor/actor systems in micro and nano regions. One Advantage for such MEMS is the technology, which directly can be applied from the micro electronics. Another one is the simple and robust layout. Disadvantages for Control are the strong nonlinearity of the electrostatic field component and the nonlinearity of fluid damping. Simulation and practical tests have to show, if the robustness of the control is still sufficient for the highly nonlinear system.

The block description shows Fig. 1, consisting of

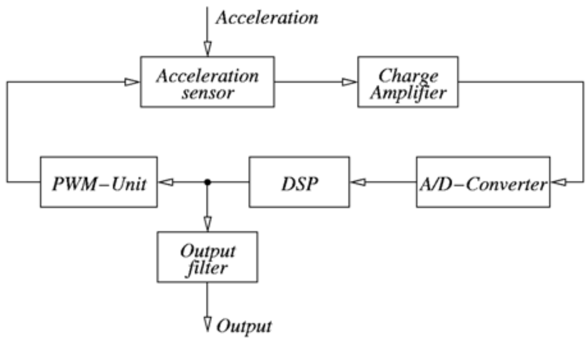


Fig. 1: System Block Diagram

the MEMS sensor, the charge amplifier, A/D conversion system, the PWM driver and DSP system.

2 Design

The sensor configuration shows Fig. 2. The sensor covers consist of glass to reduce the circuit effort in the detection electronics. The applied SiO_2-Bumpers at the edges of the seismic mass prevent the electrical contact with the outer electrodes.

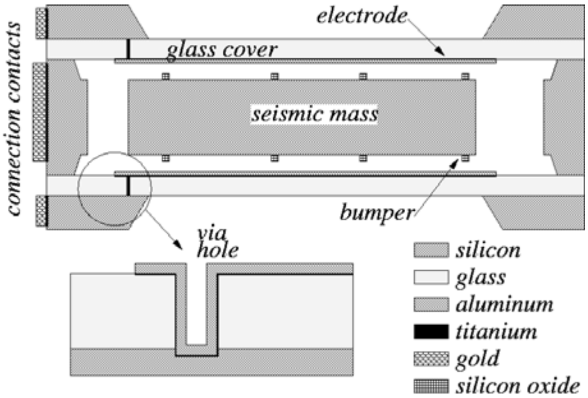


Fig. 2: Schematic configuration of the sensor chip

3 Model Building

The electrical actuated acceleration sensor can be generally described as a rotational mechanical spring-mass system

$$\left[-\omega^2 J + \mathrm{j}\omega\left(D + D_s(\omega)\right) + K + K_s\right]\varphi(\omega) = M_{ext}(\omega) + M_{el}\left(\varphi(\omega), u(\omega)\right) \quad (1)$$

with the moment of inertia J, the damping D and spring constant K, consisting of constant mechanical and frequency dependent squeeze-film parts, an acting mechanical moment M_{ext} from the outside, the electrostatic moment M_{el} and the rotation angle φ.
Just only the first torsional mode with the resonance frequency

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{K}{J}} \quad (2)$$

is controllable and detectable and is considered in the model. Since the resonance frequency can be measured easily, it is used to estimate the spring constant K, which directly specifies the DC-gain of the mechanical system.
The squeeze-film parts can be described with the *Reynolds Lubrication Equation*, a special simplification of the general *Navier-Stokes Equations* in the case of a small gap between two parallel moving plates, laminar flow and isothermal compression. Supposing that the motion of the plates and pressure variation are small, the equation can be further linearized and analytically solved, which was done in [1]. A mapping with the force-current analogy of the squeeze-film damping is described in [2]. The analytical description of the squeeze-film component was extended to a rotational motion for a variating rotation axis in [3] to describe the motion of the seismic mass.
The electromechanical moment is mainly responsible for the strong nonlinear behavior of the system. It results in the electrostatic spring softening effect at high voltage and also in a change in the open loop gain of the system. The electromechanical moment can be linearized and divided into two gain parts - The inner feedback part k_{el}, which is responsible for the spring softening and in the gain part k_u in the open loop.
The detection unit, the charge amplifier, amplifies the sensor difference capacity into a proportional voltage.
The applied sensor driver, the PWM unit, firstly governs the position of the seismic mass with changing the duty-cycle of the rectangular wave. It also realizes the charge flow for the capacity detection.
The whole LTI system model, needed for the control design, can be evaluated to

$$G_{emech} = \frac{k_u k_{pwm} k_{amp} G_{mech}}{1 - k_{el} G_{mech}} \quad . \quad (3)$$

4 Control design

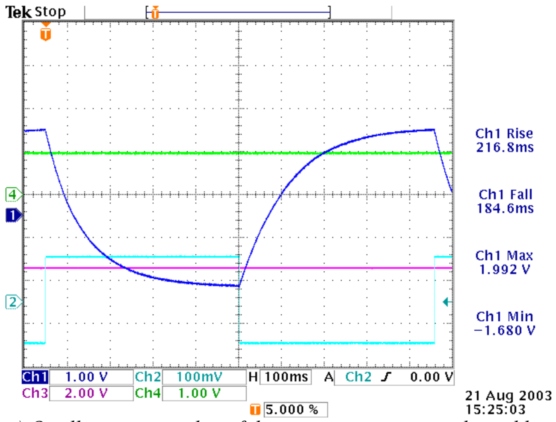
The S/KS/GS/T-Standard-Design Problem (*Mixed-Sensitivity-Approach*) is used for the control design. In this design, the transfer function matrix $\boldsymbol{N}$ will be minimized with the H_∞ Norm

$$\min_{\boldsymbol{K}} \|\boldsymbol{N}(\boldsymbol{K})\|_\infty \quad (4)$$

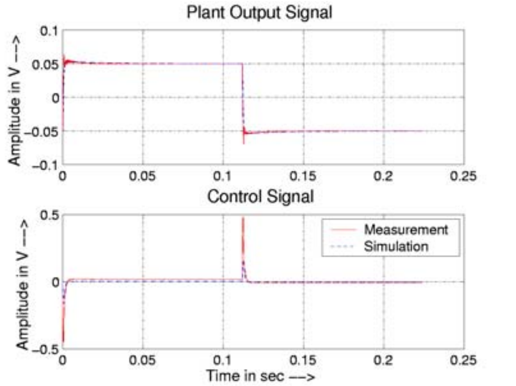
over all stable and proper controllers $\boldsymbol{K}$. In our case, the main objective is the minimization of the sensitivity transfer function $\boldsymbol{S}$, which optimizes the disturbance rejection. A constant bound is put on the control signal to further avoid actuator saturation.

5 Identification

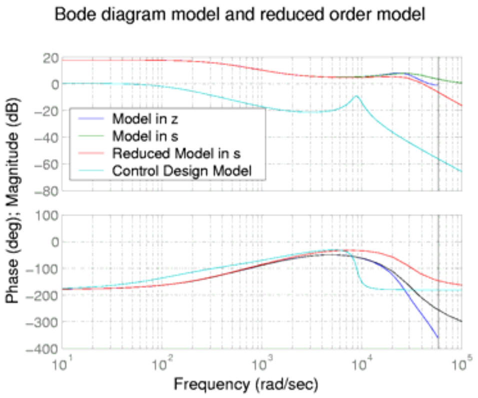
The sensor system is highly unstable under nominal operating voltage. Thus, a direct system identification is not possible in an open loop fashion way. Another way has to be found to get the system parameters from the “real world”.
In our case, the system will be identified in two stages. In the first stage a minimal sensor operating voltage $u_{b\,min}$ will be applied to the sensor. An electrostatic sensor excitation is now possible in the stable region. And the influence of the



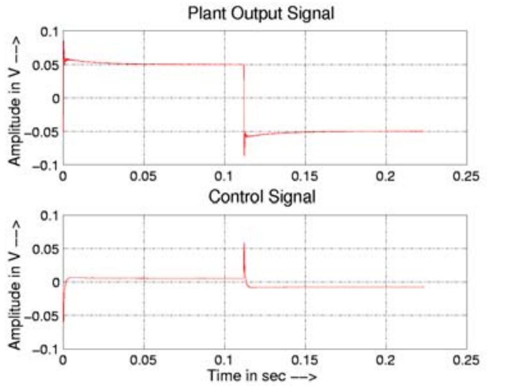
a) Oscilloscope snapshot of the sensor, operating in the stable region



b) Output and control signal of the simulation compared to the real system in- and output at operating voltage u_b = 10 V



c) Bode diagrams of the model of the second identification and the extended model of the first identification



d) Output and control signal after one iteration at operating voltage u_b = 20 V

Fig. 3: Results of one sample

electrostatic field is very low. In that case, the resulting normalized system can be equalized with the mechanical system. The control parameters will be synthesized from the extended model (3), where the field components under nominal sensor operating voltage u_b will be applied. In the second stage, another identification is made in closed-loop operation under nominal sensor operating voltage. This identification can be also seen as a system fine-tuning.

6 Results

The identification and control design routine have been successfully applied to several samples. The Results of one sample are shown in Fig. 3.

It was shown, that it is possible to control the highly nonlinear system with a robust LTI controller. The simulation of the system, shown in Fig. 4, also gives good results, which are comparable to practical tests. The controller was fond with a new introduced tow-stage identification scheme.

7 Future work

Further questions need to be answered:

- The seismic mass collision with the outer electrodes needs to be tested in simulation and practice,
- The system behavior during start up and in non-detectable regions,
- The influence of quantization effects and quantizer overflow
- System optimization, especially for resolution improvement.

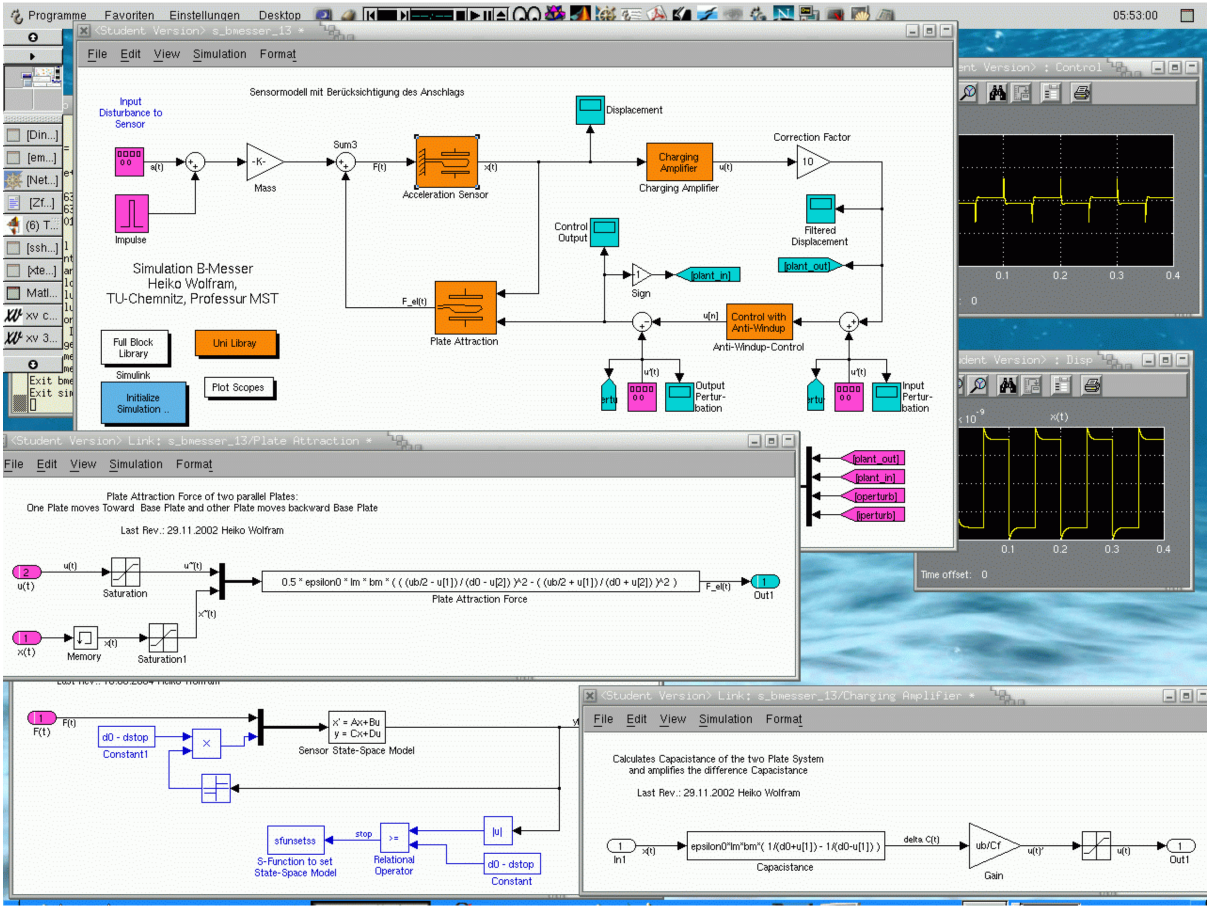


Fig. 4: Screen snapshot of the Simulink^{TM} model

References

[1] W. S. Griffin, H. H. Richardson, and S. Yamanami, *A study of fluid squeeze-film damping*, Journal of Basic Engineering, Transactions of the ASME 88, pp. 451-456, 1966.

[2] T. Veijola, H. Kuisma, J. Lahdenper, and T. Ryhnen, *Equivalent circuit model of the squeezed gas film in a silicon accelerometer*, Sensors and Actuators A 48, pp. 239 248, 1995.

[3] H. Wolfram, R. Schmiedel, S. Kurth, K. Hiller, J. Mehner, T. Aurich, W. Günther, W. Dötzel and T. Geßner, *Model Building, Control Design and practical Implementation of a high precision, high dynamical MEMS Acceleration Sensor*, to be published