MEMS Design Optimization using coupled FEM and Electrical Circuit Simulation

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ABSTRACT

The FEM (Finite Element Method) package ANSYS including the CFD (Computational Fluid Dynamics) module FLOTRAN was coupled with the electrical network simulator HSPICE for the comprehensive design of micro-systems. The coupling permits the simultaneous optimization of geometrical, mechanical and electrical design parameters of a micro-electromechanical system. The usefulness of the coupling is demonstrated by the numerical simulation of a pressure-based water flow rate meter. The device fabricated comprises a flow restriction element with incorporated piezoresistive silicon pressure sensor with on-chip circuitry, which was automatically optimized towards the desired output signal using ANSYS design optimization tools.

Keywords: CMOS integrated pressure sensor, finite element simulation, electrical network simulation, computational fluid dynamics, micro-system optimization.

INTRODUCTION

Micro-systems consist of the combination of sensors and/or actuators with related electronics forming a small system. The former are typically designed using FE modeling for thermal or mechanical problems, while for the electronics, electrical network simulators are used. However, there are no comprehensive design and simulation environments available that include both, circuit simulators and above mentioned general purpose FEM tools. Two approaches for the simulation of micro-systems have been reported before. On the one hand there is the simulation of the entire problem within one single simulation tool [1] and on the other hand a modular method. It consists of the coupling of various simulators [2] with an outer iteration for coupling and with inner solution processes for each single problem.

The coupling of HSPICE, a network simulator for electrical circuitry, and ANSYS, a widespread FEM program with so-called "multiphysics" capability is well adapted to the design and optimization of sensors integrated with analogue circuitry - one of the mayor research topics of our research center.

The interaction of sensors and their related circuitry is in most cases one-directional, i.e. the sensor output signal represents the input signal of the circuitry but the signal processing does not affect the membrane part of the sensor. Sometimes, bi-directional interaction can be found, for example, when the self-heating of the circuitry affects the sensor or in case of sensing-driving of a mechanical resonator. Only bi-directional interaction requires a coupled solution while the one-directional does not.

In fact, the objective not only was the coupling of the simulators itself but the simultaneous optimization of parameters belonging to different parts of the coupled system. In this paper, this is applied to one-directional coupling, although the approach can be applied to cases of bi-directional interaction, too. As an example, the automatic design optimization procedure of a volume flow meter containing a silicon pressure sensor is illustrated.

THE SIMULATED SYSTEM

One of the most widely used flow meters in industry is based on the measurement of the pressure difference created when forcing the fluid to flow through a restriction in the pipe. In conventional flow rate meters, the differential pressure related to the flow is measured by means of an electronic manometer externally piped to both sides of the flow restriction.

We developed an innovative compact solution, which is shown in Figure 1, incorporating a piezoresistive thin silicon membrane pressure sensor into a concentric orifice type restriction [3]. The flow meter, a photograph of the prototype is shown in Figure 2, was designed for applications in water pipes of up to 10 l/min. The generated differential pressure Δp between its inlet and outlet side shows a quadratic dependence with the volume flow rate Φ according to the equation of Bernoulli. The pressure difference is sensed by the 5.88x5.38 mm² sized gauge pressure sensor through front side and back side pressure tap connections. The sensors are anodically bonded to a glass substrate of 1 mm thickness prior to packaging. The membrane of the piezoresistive silicon sensor, 530x530 μm^2 in size and 5 μm thick, features a full Wheatstone bridge of implanted resistors which are biased at 5V dc. Corresponding to the pressure load the mechanical stress state of the sensor membrane changes and the values of one pair of piezoresistors increase whereas the other two resistor values decrease, unbalancing the Wheatstone bridge.

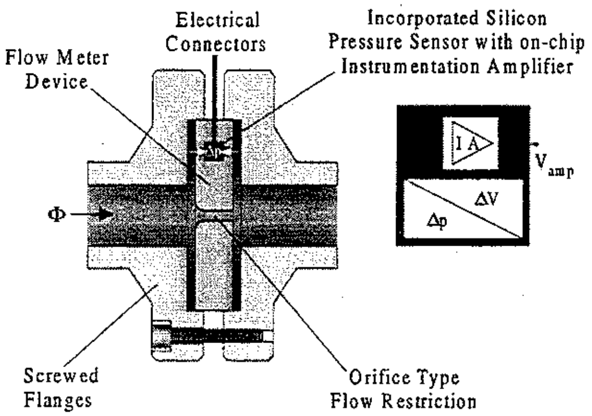

Figure 1. Principle of a flow rate meter based on differential pressure measurement

The output signal is amplified by the monolithically integrated CMOS instrumentation amplifier. A scheme of the sensor is shown in Figure 3. It was fabricated using a standard CMOS process and some additional sensor specific modules [4].

A typical design goal for such a flow meter is the optimization of the electrical output signal. This refers to the full scale output of the flow sensor system as well as to the output linearity of the silicon sensor within the pressure range. Assuming a given and fixed design of the flow restriction element which determines the relation $\Delta p = f(\Phi)$, the size of the pressure sensor membrane and the distances of the piezoresistor pairs from the membrane edge affect the sensibility $\Delta V_{bridge}/\Delta p$ and the linearity of the silicon sensor. Hence, they also influence the output of the flow sensor $V_{amp} = f(\Phi)$ and its full scale output. But the output evidently also depends on the design of the amplifier circuitry, especially on the resistor values R_g, R_1 and R_2 which determine the gain and the linearity of the amplifier. Initially, both components, the sensor and the amplifier circuitry, were designed separately. However, the optimization of the flow sensor output can hardly be achieved in this way. Therefore, program linking and automatic optimization techniques are really useful.

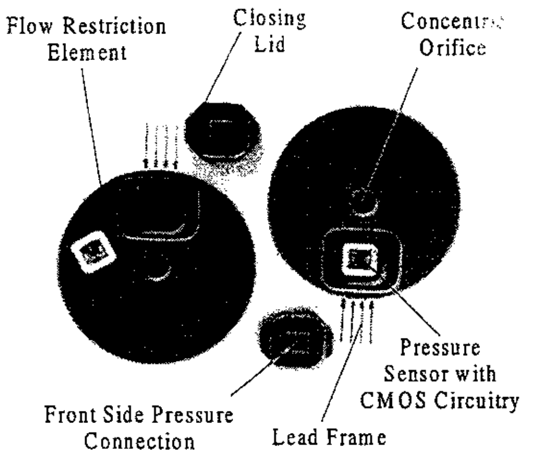

Figure 2. Photograph of the flow meter and the monolithically integrated silicon pressure sensor incorporated

THE PROGRAM COUPLING

Apart from ANSYS and HSPICE an auxiliary program called SADE (SPICE-ANSYS-Data-Exchange) was used. The program routine was written in portable ANSI C source code and after compilation it can be run on all computer systems. The operating system used was UNIX running on a HP platform. The simulation and optimization run is schematically shown in Figure 4.

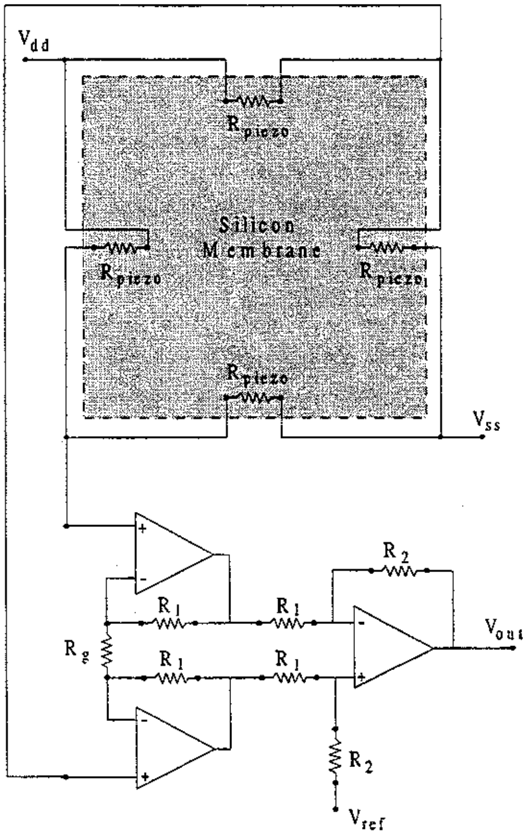

Figure 3. Scheme of the pressure sensor and the instrumentation amplifier circuitry

ANSYS is started in batch mode and the simulation begins with the generation of the FLOTRAN CFD model of the pipe with the inserted orifice type flow restriction element. A ramp of flow velocities is applied to the nodes at the inlet of the CFD model and the pressure at the outlet is set to zero.

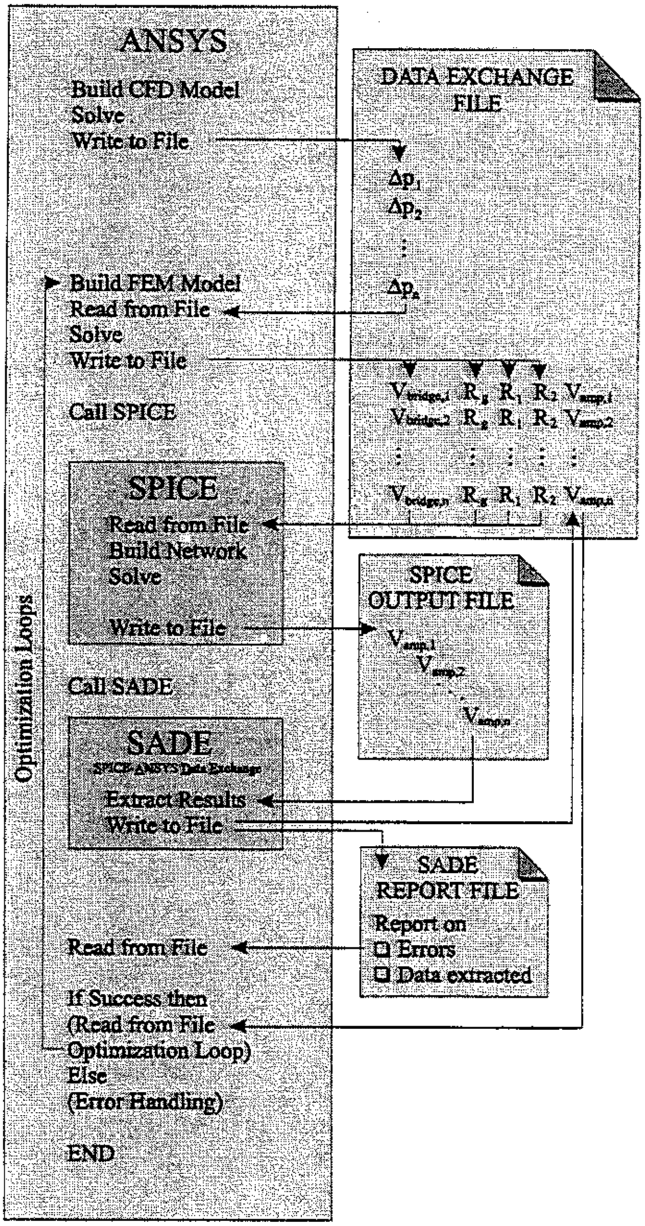

Figure 4. Schematic representation of the coupled simulation and optimization run

FLOTRAN, which forms part of ANSYS, then calculates the relative pressure distribution for the applied velocity ramp in the fluid problem domain. The resulting differential pressures between the inlet side and the outlet side of the orifice are stored in a general purpose data exchange file. Then the structural FEM analysis of one quarter of the symmetrical silicon sensor membrane is started automatically. The model is built and the array of differential pressure values is applied as loadsteps to the sensor membrane. The geometrical non-linearities and stress stiffening are considered as well as the mechanical anisotropy of silicon. The FEM problem is solved and the average of the stress components that the two piezoresistors suffer is computed. These average stress values are multiplied with the corresponding piezo-coefficients in order to calculate the resulting resistor values and the Wheatstone bridge output voltage. The output voltages along with three initial amplifier resistor values are then written to the data exchange file. The ANSYS **CFWRITE* command permits to write this file in a specified format that can be read from within a SPICE input netlist file without any modifications.

In the next step a system command is executed from ANSYS opening an X-terminal and running SPICE in batch mode. The SPICE input netlist file name of the CMOS instrumentation amplifier model is specified on the system command line as a command line parameter. The resistor values and the Wheatstone bridge output voltages of the data exchange file are read-in by the SPICE statement *.DATA*. They are now used to build the netlist as well as to index the internal simulation loops of the dc analysis. The resulting amplifier output voltages are redirected to an output file specified in one of the command line parameters and control is returned to ANSYS.

Next, SADE is executed by ANSYS. The command line parameters specify the results of the network simulation the user wants to extract from the SPICE output file and pass to ANSYS. The interface routine extracts the array of amplifier output voltages and stores it in the data exchange file using standard FORTRAN format specification. It also creates a report file, reporting successful extraction of results or encountered errors for possible error handling to ANSYS. Control is then given back to ANSYS which finally reads-in the amplified voltage values. The evaluation of each design is then done by the design optimization tool.

THE DESIGN OPTIMIZATION

ANSYS offers tools which were used for the optimization of the silicon membrane and the CMOS circuitry of the pressure sensor part of the flow meter. The optimizer executes consecutive loops changing the specified design variables in order to find an optimum design. The orifice type flow restriction was not included into design optimization although it could have been.

The aim was, beginning with the design of the pressure sensor fabricated, to find a new design which provides a flow rate sensor output of 4.5 V dc at a differential pressure of 1.5 times the one at the maximum volume flow of water of 10 l/min. This variable to be optimized during the looping is called "objective function" in ANSYS optimization terminology. The so-called independent "design variables" which were varied automatically were the membrane size of the sensor, the distances of the piezoresistor pairs from the membrane edges and the amplifier resistor values of the CMOS circuit. Additionally, other derived variables were constrained to be within certain ranges. These restrictions are called "state variables". In our case, the terminal nonlinearity of the silicon pressure sensor response was demanded to be lower than 0.5% and the total area of the chip should be smaller than that of the initial design. One of the strong features of the coupled optimization is that optimization design variables and state variables are not restricted to belong to the FE model but electrical component values of the SPICE netlist may also be included.

Figure 5 shows the evolution of the full scale output of the flow sensor with the design sets. After 26 optimization loops an optimum design was found. The full scale output of the sensor was elevated from 4.23 V dc in the initial design to 4.52 V dc at the maximum volume flow rate assumed. The silicon membrane size and all the amplifier resistors were reduced during the optimization, especially the four resistors R_1 down to 47% of its initial value. Thus, the total area required by the membrane and the amplifier resistors was reduced to 69% giving rise to a considerably smaller and more economic sensor design. In Figure 6, the simulated amplified and non-amplified output voltages of the flow sensor over the volume flow are illustrated.

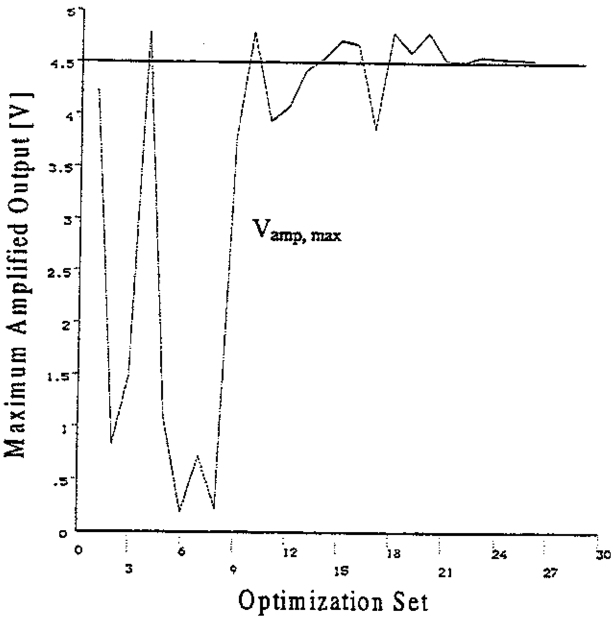

Figure 5. Evolution of the optimization objective function (amplified output voltage) with the optimization loops

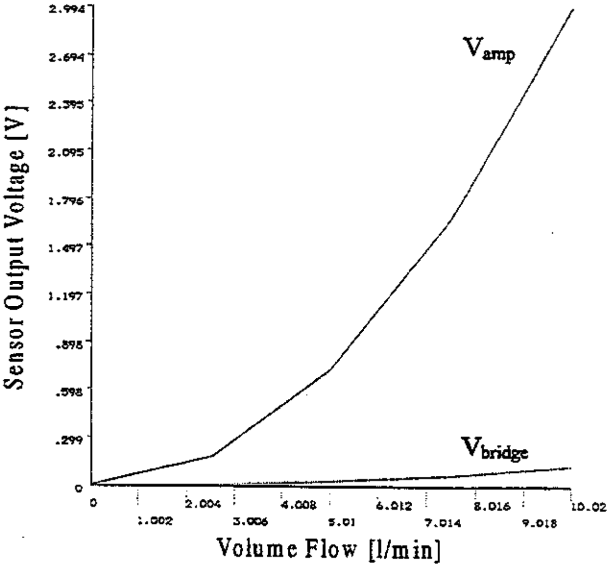

Figure 6. Simulated output voltage of the flow sensor against the volume flow

CONCLUSIONS

The program coupling presented permits the automatic design optimization of micro-systems. The

ANSYS design optimization tool was used not only to optimize the Finite Element Model but also to simultaneously find optimum values for components of the linked electrical network simulated with SPICE. Apart from the application to sensors integrated with electronics, which was taken as an example, it is also suitable for simulations where a part of the non-electric problem can be described benefiting from electrical circuit analogy.

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