Compact MEMS Modeling for Design Studies

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ABSTRACT

A method for MEMS macromodel development is presented which is based on a physical device description to obtain mathematical relations for the device operation. Since design and technology parameters are input parameters of the resulting model, this method is well suited for design studies. As a benchmark problem, we refer to the macromodel of a micropump driven by an electrostatically actuated membrane. For the calibration of the pertinent compact models, an established parameter extraction software and circuit simulator have been interlinked and, additionally, combined with new MEMS-dedicated extraction routines for quasistatic and transient analysis, thereby forming a powerful, easy-to-use analysis and design platform.

Keywords: compact modeling, parameter extraction, design studies

1 INTRODUCTION

In the field of compact MEMS modeling considerable effort has been spent in the development of methods for automated model generation [1], [2]. Relying on measured device characteristics and FEM-simulations, compact models (CM) for a given device can be generated with relatively small engineering effort. However, since the resulting CMs do not include an explicit description how the device characteristics depend on design and technology parameters, the complete model generation procedure must be repeated, whenever these parameters are varied. In particular, the effort required for providing the input data by means of experiments and FEM-simulations is usually large, which is very detrimental to the overall-efficiency of such a modeling approach.

But nevertheless, the analysis of the system dependence on design and technology parameters is a typical task for which an efficient CM strategy is needed. To this end, we suggest an alternative modeling approach.

2 MODELING APPROACH

Using the basic modeling principles as described in [3], [4] as a guideline, one starts the formulation of CMs from a physical device description expressed by mathematical relations for all relevant quantities. Often the derivation of analytical descriptions cannot avoid certain approximations; the resulting loss of model accuracy can be corrected by incorporating a small number of deliberately chosen fit parameters in the CM. But since these fit parameters have still an intuitive meaning in terms of well-defined physical effects, their impact on the simulated device behavior remains understandable. This, in turn, allows for an efficient target-oriented parameter extraction strategy, which is indispensable for improving the model accuracy. Often the model parameters can be directly extracted from the measured device characteristics, using slopes, interceptions or turn points etc., thus avoiding the problems that come with numerical error-minimizing curve fitting techniques (no global solution guaranteed, dependence on initial values, sensitivity to noisy input data, high numerical effort required). Another crucial aspect is that the parameter extraction cycles have to be passed repeatedly many times to cope with inaccurate input parameters such as material properties, e.g. That makes an efficient extraction strategy even more desirable.

Because design and technology parameters are input parameters of the resulting model, the dependences of the device characteristics on these parameters are included by construction. Provided that no important physical effect has been overlooked, the fit parameters will - by construction - show a weak dependence only on design and technology variations. That is why such CMs are well suited for design studies.

Additionally, as all parameters allow a physically transparent interpretation, it proves advantageous to use such models for statistical modeling and yield/failure analysis.

3 APPLICATION EXAMPLE

To illustrate the above-described modeling methodology, we refer to the macromodel of a micropump driven by an electrostatically actuated membrane. For small deflections of the drive membrane, the relation between applied hydrostatic and electrostatic pressure on the one hand and the resulting membrane deflection on the other hand can be expressed analytically. For large deflections, even though analytical descriptions are known, we deliberately used a simple fit function to account for the resulting non-linearities. The corresponding fit parameter was extracted from comparison with FEM-simulations. This approach preserves high accuracy even in the region of large deflection (Fig. 2). The nonlinear relation between membrane displacement and electrostatic attracting force causes the well-known snap effect.

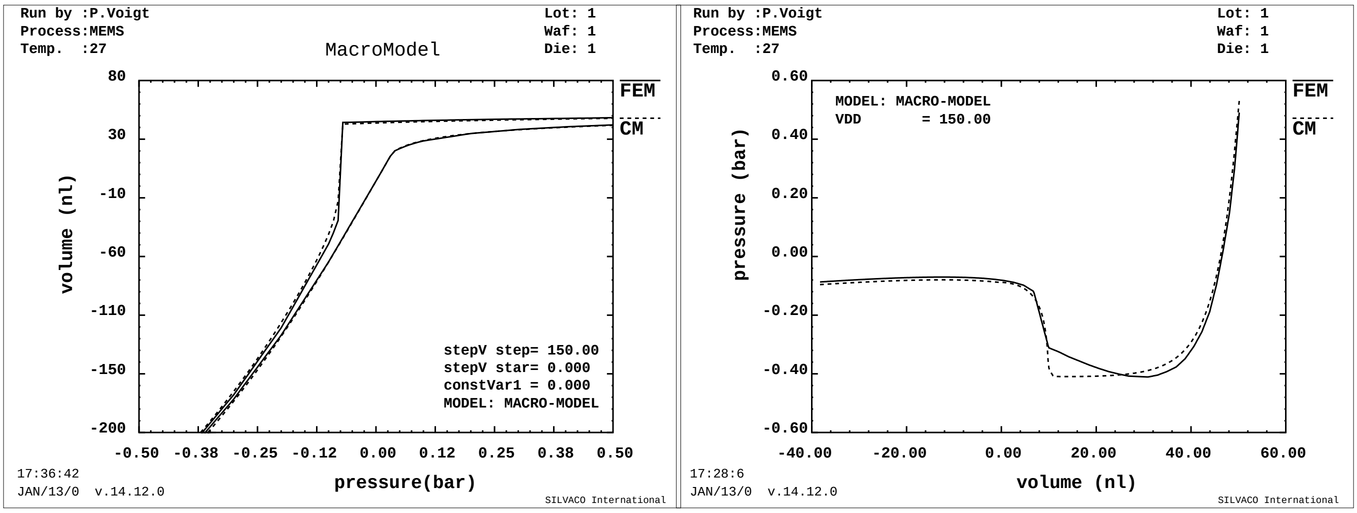

Figure 1: Results of parameter extraction for the quasistatic characteristics of an electrostatically deflected membrane. When pressure is controlled, an applied voltage of 150V causes snap-in (left). When the volume is forced (right), a sudden change in the membrane's bending shape causes a discontinuity in the device characteristics.

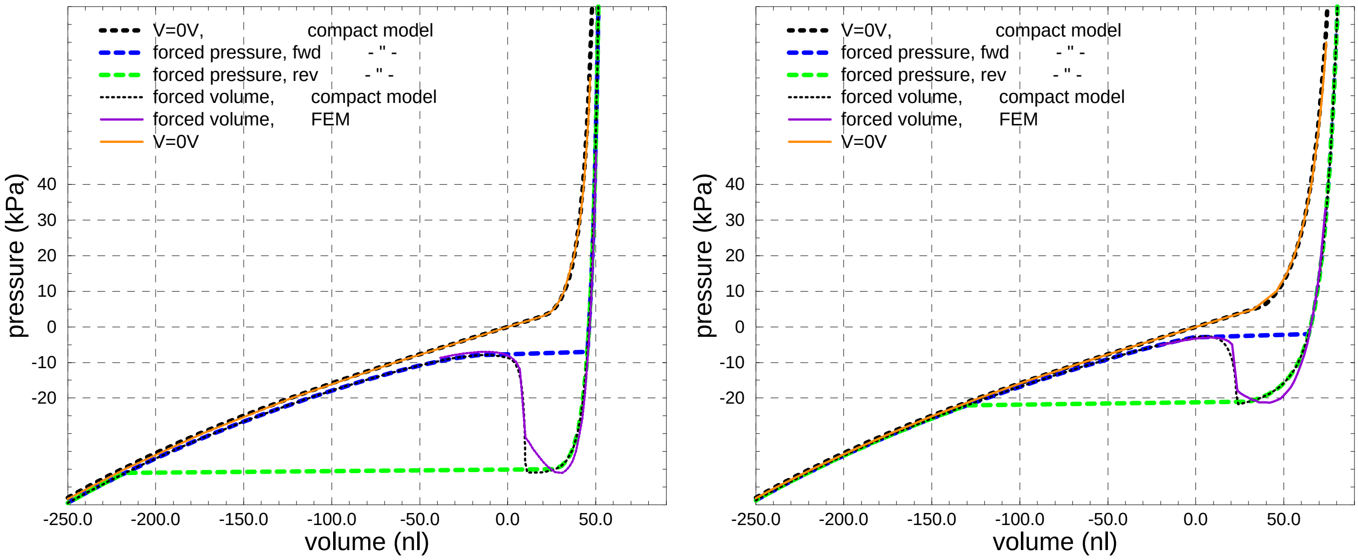

Figure 2: Simulated static characteristics (hydrostatic pressure vs. displaced volume) of an electrostatically deflected membrane. Dotted/dashed lines: CM, solid lines: FEM. A voltage of 150 V is applied to the membrane, causing the well known snap effect. The fitting parameters of the device model are extracted from a membrane with 3μm gap width (left), then applied to a membrane with 5μm gap width (right). The achieved accuracy for the 5μm device shows the extrapolation capabilities of the underlying device model.

To access the instable part of the volume-versus-pressure characteristics, one has to change from pressure control to volume control (fig. 1, right). These characteristics also show a discontinuity, caused by an abrupt change in the shape of the membrane deflection. To accurately capture the correct snap conditions, a fit parameter was introduced in the model and was determined by means of parameter extraction from FEM-simulated data (fig. 1).

To test the extrapolation capabilities of the developed membrane model, a design parameter - namely the gap width between membrane and counterelectrode - was varied from 3 to 5μm. Using the same physical model parameter set for the modified device we still find the model to be very accurate (Fig. 2), corroborating the aforementioned statement that our modeling strategy is best suited for design studies. Both the optimized 3μm gap model and the extrapolated 5μm gap model have been used to simulate the frequency-dependent pump rate of the micropump as reported in [5]. It shows that both models accurately describe the device operation (see Fig. 4).

In order to reproduce also the transient behavior of the micropump correctly, in particular the peculiar effect of reverse pumping, the valve flap compact model must cover dynamic effects as well. Fig. 3 shows the transient response of a flap valve to a step-like change in pressure. In the developed CM, three model parameters had to be extracted from a comparison with FEM-simulated data (coupled simulation of fluid-structure interaction): linear and quadratic damping terms, and the mass of the fluid which is dragged by the moving flap.

The CMs for the membrane, the valves and all other constituent parts of the micropump were coded in VHDL-AMS [6]. For model parameter extraction, a commercial extraction software package [7] was extended in such a way that all parameters of the VHDL-AMS models could be extracted straightforwardly. This necessitated the development of an VHDL-AMS capable interface to a circuit simulator as well as the development of MEMS dedicated extraction routines for quasistatic and transient analysis.

4 CONCLUSIONS

We presented a strategy for the compact modeling of MEMS devices which, due to the explicit implementation of the dependences between device characteristics and design and technology parameters, allows for the inter- and even extrapolation in the space of design parameters. In the resulting compact models, the parameters have a distinct physical meaning, thus allowing to set up an efficient parameter extraction strategy.

The required interfaces between simulation and parameter extraction software have been developed, as well as parameter extraction routines for quasistatic and transient analyses. The resulting tool set enables parameter extraction, statistical modeling and yield/failure analysis for multi-energy domain systems such as MEMS on the same sophisticated level of accuracy as for standard electronic devices in integrated circuits.

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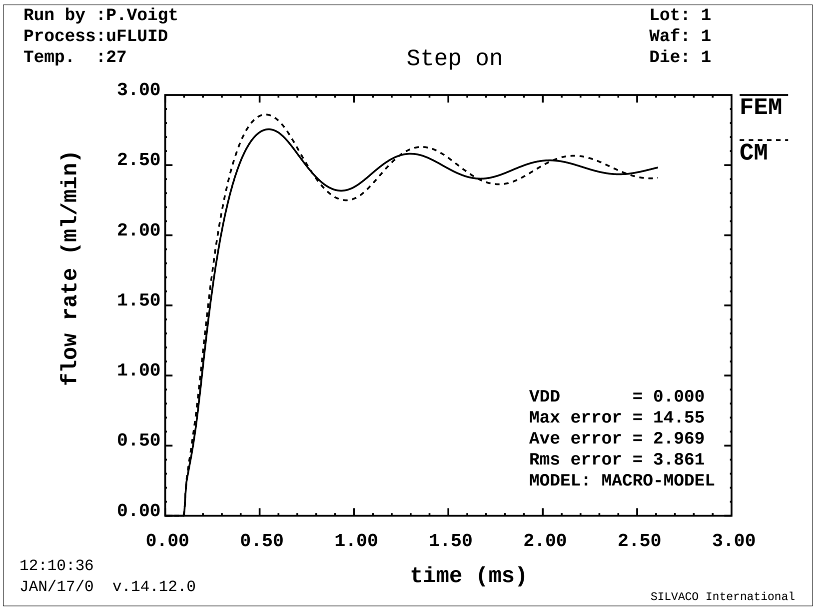

Figure 3: Intermediate results of a parameter extraction for the transient pressure step response of a flap valve. The steplike pressure change causes a damped oscillation of the valve flap, leading to a new equilibrium position. The flow rate through the valve has contributions from a quasistatic flow, dependent on the flap position, and from a dynamic flow, namely a volume displacement dependent on the flap velocity.

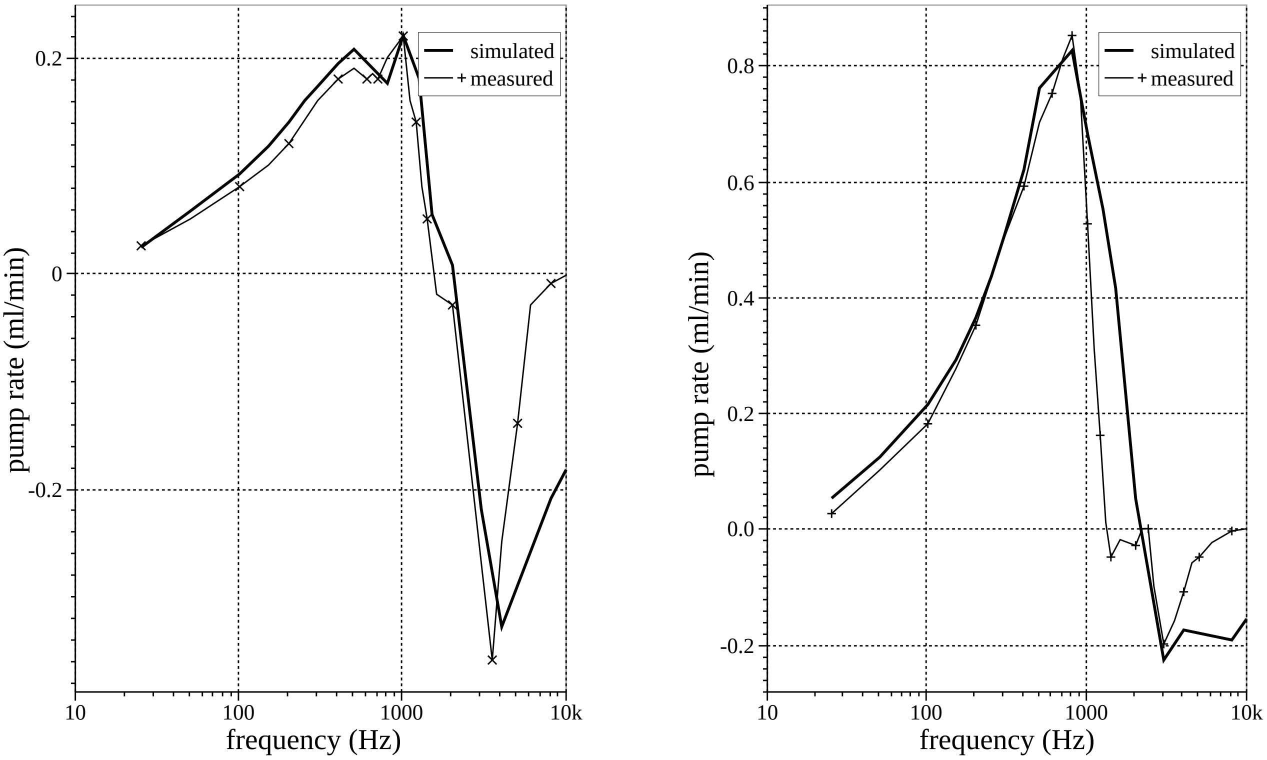

Figure 4: Frequency-dependent pump rate of a micropump with a 3μm (left) and 5μm gap width (right) of the drive membrane. In both cases the same set of fitting parameters for the membrane model was used.