Modelling of Silicon Microphone Systems

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Introduction

In recent years system simulation has been a permanent part of product development, and has become more and more important within microsystem technology, since with it, development processes can be notably accelerated. Thus, models will be required to simulate the behaviour of microsystems appropriately. With the help of these models, prognoses regarding the expected system behaviour are possible, providing information on how constructive modifications may influence the behaviour of the targeted microsystem application. In this publication the modelling of a silicon microphone will be described. Moreover, a modelling environment developed for the investigation of the microphone and its constructive parameters will be introduced.

Description of Microphone Model

Electro-acoustic sensors such as the CMOS–compatible, capacitive microphone in silicon technology discussed here, transform a receiving acoustic signal via two energy conversions into an electric signal (Fig. 1).

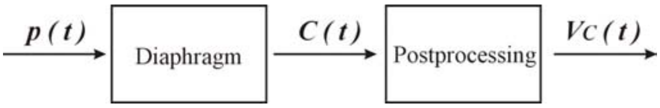

Fig. 1: Electro-acoustic Conversion Process

In the first step, an acoustic-mechanical conversion of the impinging air pressure signal *p(t)* is performed with the help of a thin diaphragm. Its oscillation causes a temporal variation of the electrical capacitance *C(t)* that is due to the diaphragm and the backplate electrode. This variation of the capacitance is easily detected and post-processed by an electrical circuit and converted to an alternating voltage $V_C(t)$. This second step corresponds to a mechanical-electrical energy conversion.

According to these two conversion stages the total sensitivity S of the sensor is due to a mechanical sensitivity S_m and an electrical sensitivity S_e,

$$S = S_m \cdot S_e \tag{1}$$

The electrical sensitivity S_e goes in as a statistical transfer factor, since the electrical circuitry ensures that a voltage change is immediately proportional to a change within the air gap of the microphone.

To determine the frequency dependent mechanical sensitivity S_m of the microphone, a relation between the deflection of the diaphragm and the acoustic pressure is required. The following equivalent electrical circuit model simulates the mechanical behaviour of the microphone.

Structuring of the System

For modelling purposes, the sensor will at first be hierarchically structured. That is, the whole silicon microphone system will initially be partitioned in several subsystems, which in turn are subdivided as necessary. In doing so, the overall modelling task is reduced into several subtasks, that are easier to manage. The corresponding subsystems are defined in Fig. 2.

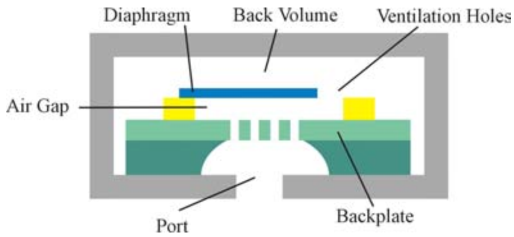

Fig 2: Schematic Diagram of Silicon Microphone

Modelling of the Subsystem Diaphragm

As an example for the modelling process focus will be on the representation of the subsystem diaphragm. For small deflections the behaviour of a real diaphragm may be described by the superposition of two equivalent models with idealised properties [1]. In general, the term diaphragm corresponds to both, an ideal membrane as well as an ideal thin plate, with the radial deflection profiles differing fundamentally in that the reset forces are due to different physical phenomena.

The term ideal membrane refers to a diaphragm with a large initial tensile stress σ_{res}, and accordingly the energy due to bending can be neglected. That means, deflection is mainly determined by that stress, when loaded. In contrast to this, an thin plate is free from any initial stress, having a deflection that is only determined by the flexural rigidity of the diaphragm if loaded. This is indicated in Fig. 3.

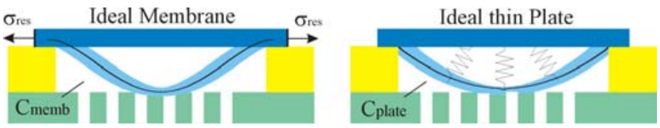

Fig. 3: Deflection Behaviour of Ideal Diaphragm

In order to determine the compliances C_{memb} and C_{plate} of round diaphragms for small deflections a simple linear correspondence between the middle deflection and an area load P (static acoustic pressure) can be assumed. The compliances in both cases, ideal membrane and ideal thin plate may be well estimated by [1]

$$C_{memb} = \frac{\pi \cdot a^4}{4 \cdot \sigma_{res} \cdot h} \tag{2}$$

$$C_{plate} = \frac{0.18 \cdot (1-\nu^2) \cdot a^6}{E_d \cdot h^3} \qquad (3)$$

In these equations a refers to the radius of the diaphragm, h represents thickness of the diaphragm, E_d is the elastic modulus of silicon and σ_{res} corresponds to the internal restraint of the diaphragm.

For the description of the real behaviour of a diaphragm in the case where both phenomena are present, a series connection for both compliances may be chosen. Accordingly, the overall compliance C_{dia} is determined by the dominating effect and results obviously into

$$C_{dia} = \frac{C_{plate} \cdot C_{memb}}{C_{plate} + C_{memb}} \qquad (4)$$

In addition to the spring property of the diaphragm, the acoustic mass m_{dia} of the diaphragm has to be taken into account. This is indicated in the equivalent circuit shown in Fig. 4 as a series combination of m_{dia} and C_{dia}.

The combination of the equivalent electrical circuits of the substructures, derived in similar manner, to a network representing the overall behaviour is shown in Fig. 4.

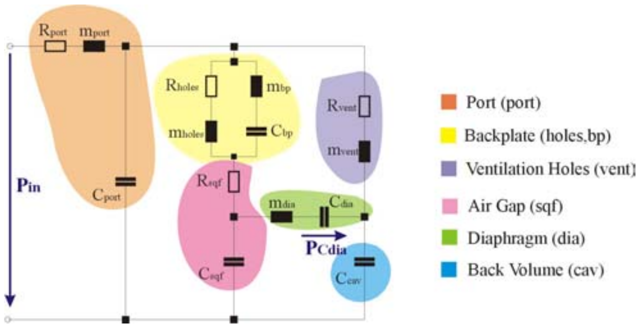

Fig. 4: Structure of Overall Model

Modelling Environment

The overall model was implemented in Matlab, together with a modelling environment, which allows for easy parameterisation of the model. Moreover, the environment facilitates investigations on variations of the structure. The modelling environment is shown in Fig. 5.

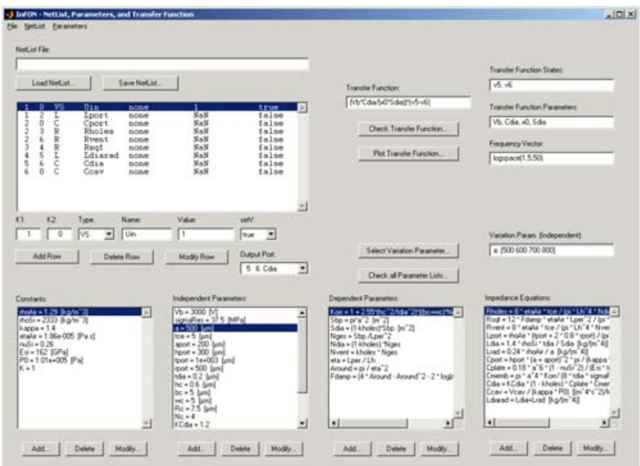

Fig. 5: Modelling Environment – Silicon Microphone

In the upper left area the structure is represented in terms of a net-list. In the upper right area transfer functions for the components of the net-list may be specified via the corresponding equation. Moreover, the frequency range of interest may can be defined. In the bottom area the model parameters, dependent as independent, and the parameter equations are listed.

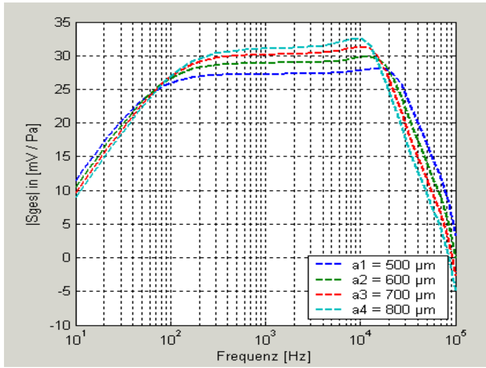

Fig. 6: Sensor Sensitivity subject to Variation of Diaphragm Radius

In Fig. 6, the simulated sensitivity of the output signal of the sensor subject to a variation of the radius of the diaphragm radius is shown. As could be expected the size of the diaphragm is directly proportional to the sensitivity of the microphone, whereas the larger diaphragm radii tend to be less sensitive in the higher frequency ranges, thus, reducing the applicable bandwidth of the microphone.

Summary

The modelling procedure described in this publication based on a partitioning of the total structure allows a synthesis of the overall transfer function from simple, physics-motivated equations representing the behaviour of the substructures. Casting this into a Matlab description admits relatively easy combination with a GUI in order to obtain a modelling environment convenient for parameter studies during the development process.

In addition to the omni-directional microphones discussed in this publication for simplicity the modelling procedure was also successfully applied to bi-directional microphones, showing the versatility of the approach.

References

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The work was performed under sponsorship of the German ministry of education and research (BMBF) under grant no. 16SV1273. The responsibility for this publication is with the authors only.