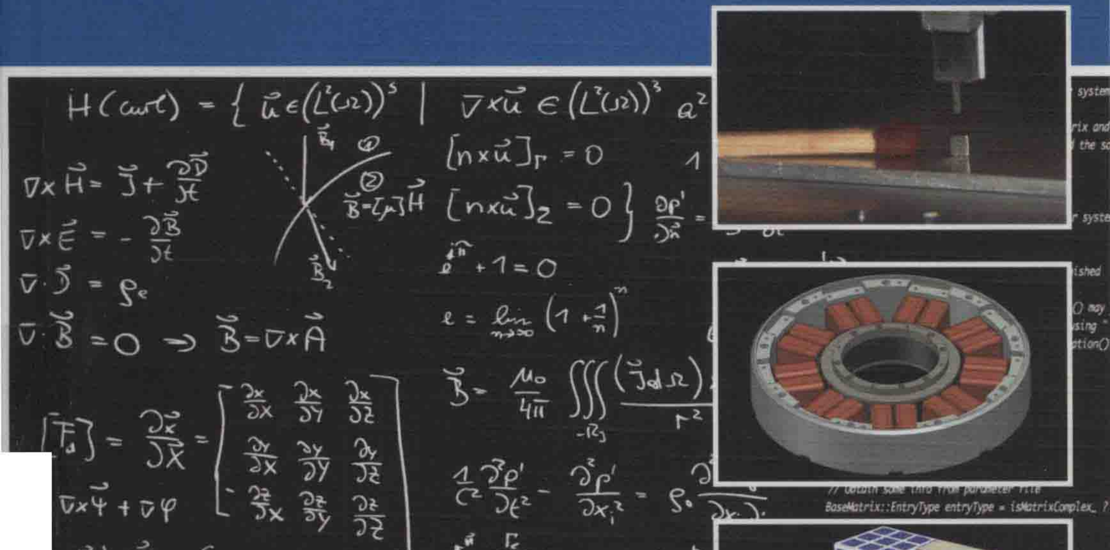
Measurement-, Actuator-, and Simulation-Technology

Modeling and Optimization Methods of an Electrostatically driven MEMS Speaker



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Modeling and Optimization Methods of an Electrostatically driven MEMS Speaker

DISSERTATION

To obtain the Academic Degree

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Institute of Mechanics and Mechatronics

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"The task is...not so much to see what no one has yet seen; but to think what nobody has yet thought, about that which everybody sees."

Erwin Schrödinger
1887 - 1961

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Abstract

The market for battery powered devices, such as smart-phones or tablets increases rapidly. The trend goes towards smaller and thinner cases. The main challenge is to decrease the power consumption by coincidently shrinking the device size and increasing the efficiency. Micro-electro-mechanical-systems (MEMS) manufactured of silicon, merge cost effective and space saving features as an energy efficient and innovative product. In this work, reversible operated silicon microphones are modeled and optimized towards sound pressure level and total harmonic distortion. The models are described by coupled partial differential equations and solved by the help of the finite element method. Due to the small dimensions of a single acoustic transducer of approximately one millimeter in diameter and two micrometer in thickness, the loudspeaker is manufactured as an eight bit array. The array arrangement opens up the opportunity to drive the speaker in conventional analog driving mode or apply digital sound reconstruction. Geometric nonlinearities such as large deformation, pre-stress or mechanical contact are reflected in the mechanical model and excited electrostatically. By applying the virtual displacement method, the influence of the insulation layer is mapped to the electrostatic force computation. The electrostatic force interacts with the structural mechanics and the membrane starts to oscillate. The electrostatically actuated membrane is coupled to the acoustic model, where the sound pressure level is computed. The challenge in the acoustic propagation computation is on the one hand, the number of unknowns, which can be minimized by using Mortar FEM (non-conforming grids), and on the other hand, in the reflections caused by the bounds of truncating the propagation region. These reflections are minimized with absorbing boundary conditions or a perfectly matched layer surrounding the propagation region. Acoustic results on the single transducer were computed by the finite element method, where for the full speaker array a specially developed wave field computation software was used based on the Kirchhoff-Helmholtz integral. In addition, two optimization strategies towards increasing the sound pressure level were presented. The first deals with stress-induced self raising of the back plate structure, to increase the volume flow and sound pressure level. The second deals with the digital sound reconstruction, investigating the non-reset, with-reset and latched method.

Kurzfassung

Der Markt an Batterie betriebenen Geräten wie Smartphones oder Tabletts nimmt stark zu. Der Trend geht immer mehr in Richtung schlanker und dünner Gehäuse. Um die Laufzeit dieser Geräte bei gleichbleibender, oder sogar schlankerer, Gehäuseform zu verlängern, ist es wichtig energieeffiziente Bauteile zu verbauen. Silizium gefertigte mikro-elektro-mechanische Systeme (MEMS) verbinden kostengünstige und platzsparende Eigenschaften als energieeffizientes und innovatives Produkt. In dieser Arbeit werden reversibel betriebene Silizium-Mikrophone modelliert und hinsichtlich Schalldruckpegel und Signalqualität optimiert. Die Modelle werden mit Hilfe von gekoppelten partiellen Differentialgleichungen beschrieben und mit der Methode der Finiten Elemente gelöst. Auf Grund der geringen Dimensionen eines Einzelwandlers von zirka einem Millimeter Durchmesser und zwei Mikrometer dicke, werden die Lautsprecher in einem acht Bit Array betrieben. Der Array-Betrieb ermöglicht zusätzlich neben analogen Betriebsmoden, auch Untersuchungen der digitalen Schall-Rekonstruktion. Geometrische Nichtlinearitäten, wie große Verformung, Vorspannungen oder mechanischer Kontakt werden im mechanischen Model abgebildet und elektrostatisch angeregt. Mit Hilfe der virtuellen Verschiebung wird der Einfluss von Isolationsschichten auf den elektrostatischen Kraftbeitrag abgebildet. Die elektrostatisch angeregte Membran resultiert in einer mechanischen Bewegung und koppelt in ein akustisches Model. Die Herausforderung im akustischen Ausbreitungsgebiet liegt einerseits in der Anzahl der Unbekannten, welche durch Anwendung von Mortar FEM (nichtkonforme Gitter) minimiert werden können, und andererseits in den Reflexionen an den Randbereichen der Ausbreitungsregion. Diese Reflexionen werden mit absorbierenden Randbedingungen oder einem zusätzlichem Gebiet mit dämpfenden Eigenschaften minimiert. Für akustische Berechnungen am Einzelwandler, werden die Finite Elemente Methode angewendet, wobei für akustische Berechnungen des gesamten acht Bit Arrays wird ein eigens entwickeltes Wellen-Feld-Berechnungs-Tool, basierend auf dem Kirchhoff-Helmholtz Integral angewendet. Zusätzlich werden zwei Optimierungsstrategien vorgestellt. Die Erste beschäftigt sich mit Stress induzierten Buckeln der Gegenelektrode, was eine flache kostengünstige Fertigung ermöglicht und gleichzeitig den Schalldruck optimiert. Die Zweite beschäftigt sich mit der digitalen Schallerzeugung.

Contents

CHAPTER 1

1 Introduction

This research topic is originated from a cooperation between *Infineon Technologies AG Munich*, *Carinthian Tech Research (CTR) GmbH* and the *University of Technology Vienna*. The purpose of this thesis is the development of a MEMS speaker derived from the inversely driven silicon microphone (MEMS microphone E2120M; can be found in final product with package and ASIC: SMM310).

1.1 Motivation

The market for mobile devices like laptops, tablets or mobile phones is increasing rapidly. Device housings get thinner and energy efficiency is more and more important for battery powered devices. E.g., Micro-Electro- Mechanical- Systems (MEMS) loudspeakers, fabricated in complementary metal oxide semiconductor (CMOS) compatible technology merge energy efficient driving technology with cost economical fabrication processes. The major disadvantages of conventional electro-dynamic speaker systems like size in dimension, complexity in fabrication and efficiency are the advantages of the electrostatically actuated MEMS speaker. The design and evaluation process of such electrostatic CMOS MEMS speakers is time consuming and expensive, but can be supported and optimized with computer aided engineering methods. The accurate modeling of such MEMS devices results in a system of coupled partial differential equations (PDEs) describing the interaction between the electrostatic, mechanical and acoustic field. By applying the finite element method (FEM) the physical domains and their interactions can be solved.

Sound pressure level can be increased by increasing surface area, membrane stroke level and frequency. The limitation of stroke level is given by manufacturer side, due to etching processes. The limitation in surface area is given by consumer, because the smaller the MEMS speaker, the easier to apply to new products. The third limitation is given by frequency directly by human auditory. The challenge is now to combine these three factors within their bounds and optimize it towards sound pressure level and total harmonic distortion.

The main goal of this thesis is finding an accurate model, describing the physical behavior of the E2120M silicon microphone and optimize it towards generating high sound pressure level and total harmonic distortion. By the help of computer aided engineering, the fabrication and manufacturing of new structures and ideas towards a MEMS speaker system should be supported. All models have to be optimized primary for accuracy and physical field interactions and secondary on computational time and amount of memory. Hence, driving concepts, like the digital sound reconstruction of snap-in can be trimmed towards increasing the sound pressure level.

1.2 Current Status of Research

In the field of MEMS micro- speakers a differentiation between in ear applications and free field applications can be done. Requirements of in ear applications are focused on low total harmonic distortion with coincidently small physical dimensions and low energy consumption, while free field applications are designed to obtain high sound pressure levels allowing larger surface areas.

Conventional free field applications are mostly based on the electro dynamically driving principle, hence they constitute quasi state of the art in MEMS speaker for mobile applications. It is called "quasi state of the art", because integrated solutions based on electrostatic driving principle are a rapidly growing field on a new market of MEMS speakers. Some examples for electro-dynamic MEMS speakers can be found in [1-7] for circular shaped membranes and in [8] for rectangular membrane designs. Going towards integrated speakers, opens up the opportunity to design small transducer arranged is arrays, as described by [5, 7, 9, 10]. As mentioned before, the electrostatic MEMS speaker is an increasing driving technology, therefore papers and patents about various fabrication and processing steps can be found in [11-17], but no marked-ready products are available yet. Basic information on research of standard electrostatic speakers can be found in [18-20], in the range of human auditory (20 Hz to 20 kHz [21]), or in [22] for an ultrasonic transducer CMUT application in the frequency range of 60 kHz to 160 kHz. Since standard electrostatic speaker systems with single ended composition are highly nonlinear, signal pre-distortion is an important point, as discussed in [23] generally on single speakers and in [24] specialized on speaker arrays, taking wave propagation properties into account. In 2003 the idea of integrated speaker arrays came up by [25, 26] and [27], followed by basic working principle of digital sound reconstruction [28, 29]. Piezoelectric speakers form the third MEMS speaker driving technology, for single frequency buzzers, up to wide frequency speaker systems. Wide frequency in this context is referred to human auditory. Most actuators show square shaped membranes [30-32], oscillating cantilevers [33] or octagonal shaped structures [34], but all of them are single speaker investigations.

The second field of application is represented by in ear applications. The in ear micro speaker has to fill a small cavity of sound, which represents the in ear volume of the human ear canal, called the auditory meatus. Therefore, the emitted sound pressure level of these speaker systems have not to be as high as the free field applications. Dedicated research on in ear applications or hearing aids can be found in [35-39].

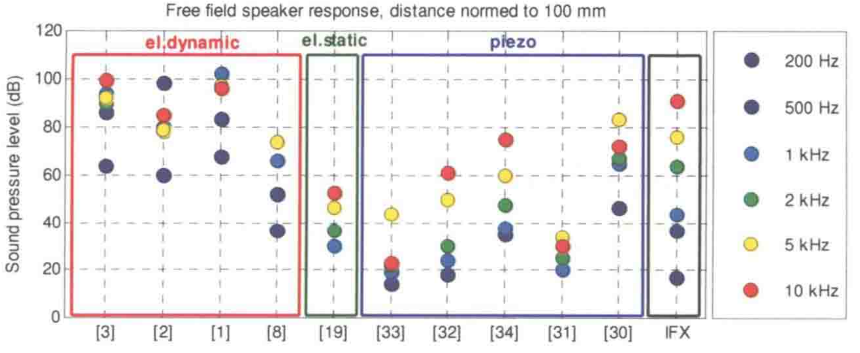

Figure 1-1: SPL comparison of electrostatic, electrodynamics and piezo MEMS speakers at a distance of 100 mm [40].

A detailed overview and comparison of the three driving technologies (electrostatic, electro-dynamic and piezo) is given in [40]. A comparison of the maximum sound pressure level on free field MEMS speakers at a distance of 100 mm, is depicted in Figure 1-1. IFX is our MEMS speaker array, consisting of 255 speaker elements.

1.3 Thesis Specification

In this thesis models have to be developed to describe the working principle of the current MEMS micro speaker used. The current micro speaker is a micro electro mechanical capacitive microphone, which is used as an inverse transducer to generate sound. Focus of this thesis is the evaluation of mechanical and acoustic behavior and describing these physical components within a finite element model (FEM). In addition investigations have to be done for analogue and digital sound reconstruction (DSR) used in single speaker cells or aligned in arrays. The leading thought behind an array usage is the increase of sound pressure level by increasing the active area, so the array method is a fundamental way for digital sound reconstruction. The inverse operated microphone is an electro statically driven MEMS which can be fabricated in CMOS technology easily, cheap and in big lots, therefore it is a very interesting technology for semiconductor industry. Focus of this work will be the evaluation of a model beginning at a control voltage up to the output sound pressure level (SPL) at any distance. Additionally, an analog eight channel MEMS speaker driver called "demonstrator" has to be developed, to be able to investigate digital sound reconstruction, sound pressure levels, total harmonic distortion and pre-distortion in the input voltage.

1.4 Structure of the Thesis

Chapter 1: An introduction on the field of MEMS speakers is given, with respect to electro-dynamic, electrostatic and piezo speaker systems.

Chapter 2: This chapter introduces basic terms regarding driving principle like single ended and push-pull or pull-pull systems, followed by the difference between analog and digital sound reconstruction. In addition to this the advantages and disadvantages of the snap-in mode