Virtual Prototyping of Electrodynamic Loudspeakers by Utilizing a Finite Element Method

Reinhard Lerch[a], Manfred Kaltenbacher[a] and Martin Meiler[b]

[a]Univ. Erlangen-Nuremberg, Dept. of Sensor Technology, Paul-Gordan-Str. 3/5, 91052 Erlangen, Germany
[b]Simetris GmbH, Am Weichselgarten 7, 91058 Erlangen, Germany
reinhard.lerch@lse.eei.uni-erlangen.de

In this paper the applicability of an efficient numerical calculation scheme in the computer-aided-design of magnetomechanical actuators is demonstrated. Practical devices, which are considered here, are electrodynamic loudspeakers. The newly developed software tool NACS is based on a Finite-Element-Method (FEM) and allows the precise calculation of the electromagnetic, mechanical as well as acoustic fields and considers all coupling terms between the different physical quantities. Furthermore, nonlinear effects in the mechanical and magnetic behavior are taken into account. Therewith, the complex dynamic behavior of electrodynamic loudspeakers can be studied and, furthermore, an appropriate computer-aided-engineering (CAE) environment including an optimization of critical parameters can be established.

1 Introduction

To reduce the efforts in the development of electrodynamic loudspeakers, precise and efficient computer modeling tools have to be used. With these computer simulations, the costly and lengthy fabrication of a large number of prototypes, required in optimization studies by conventional experimental design, can be reduced tremendously. Therefore, the need for appropriate numerical simulation tools based on finite element methods arises. As input parameters these methods require only the precise geometry of the loudspeaker as well as material data of each part.

While equivalent circuit representations suffer from appropriate input data, the main reason for the lack of computer simulation tools based on finite element methods is the high complexity of an electrodynamic loudspeaker, as shown in Fig. 1. A cylindrical, small light voice coil is suspended freely in a strong radial magnetic field, generated by a permanent magnet. The magnet assembly, consisting of pole plate and magnet pot, helps to concentrate most of the magnetic flux within the magnet structure and, therefore, into the narrow radial gap. When the coil is loaded by an electric voltage, the interaction between the magnetic field of the permanent magnet and the current in the voice coil results in an axial Lorentz force. The voice coil is wound onto a former, which is attached to the rigid, light cone diaphragm in order to couple the forces more effectively to the air and, hence, to permit acoustic power to be radiated from the assembly. The main function of the spider and the surround is to allow free axial movement of the moving coil driver, while non-axial movements are suppressed almost completely.

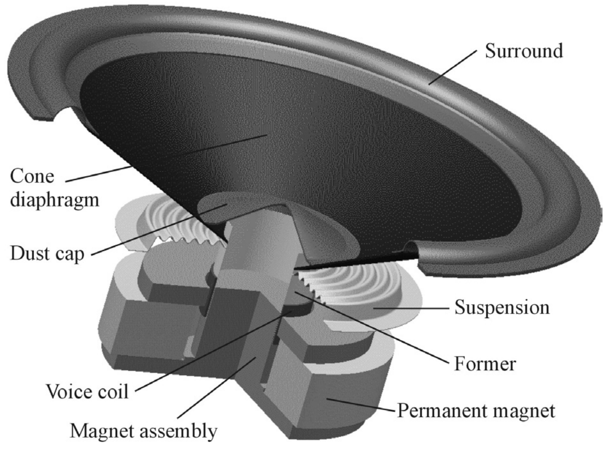

Figure 1: Schematic of an electrodynamic loudspeaker.

Since in the case of a loudspeaker the interaction with the ambient fluid must not be neglected, the electrodynamic loudspeaker represents a typical coupled magnetomechanical system immersed in an acoustic fluid. That is the reason, why for the detailed finite element modeling of these moving coil drivers the magnetic, the mechanical as well as the acoustic fields including their couplings have to be considered as one system, which cannot be separated. Furthermore, electrodynamic loudspeakers in the low-frequency range show under large-signal conditions a strong nonlinear behavior, which is caused mostly by two factors - the nonhomogeneity of the magnetic field in the air gap, i.e. magnetic nonlinearities, and the nonlinearity of the suspension stiffness, i.e. mechanical nonlinearities. These nonlinearities are caused by the large vibration amplitudes, especially at low frequencies. For large input powers the distortions increase rapidly and reach the same order of magnitude as the fundamental. Therefore, to obtain a full description of the dynamical behavior of electrodynamic loudspeakers, all nonlinearities must also be considered.

Due to the complex interactions of different design-parameters, coupled physical fields as well as nonlinearities, the straight forward application of standard simulation tools like commercially available finite element codes has shown only limited success. Therefore, in this paper, a new simulation scheme for electrodynamic loudspeakers is introduced, which has been implemented in the multiphysics software tool NACS [1]. The main focus of this article will be the demonstration of the practical usability of this scheme within the industrial computer-aided engineering of electrodynamic loudspeakers.

2 Governing Equations

For the computer simulation of an electrodynamic loudspeaker, the following physical fields have to be modeled:

2.1 Magnetic field

The governing equation describing the magnetic part of magnetomechanical systems can be derived from Maxwell's equations. Due to the solenoid magnetic field, the magnetic flux density $\vec{B}$ can be expressed as the curl of the magnetic vector potential $\vec{A}$

$$\vec{B} = \nabla \times \vec{A}. \tag{1}$$

In the case of low frequencies (neglecting displacement current), the magnetic field is described by the partial differential equation [2]

$$\nabla \times \left(\frac{1}{\mu} \nabla \times \vec{A} \right) = \vec{J}_{\mathrm{e}} - \gamma \frac{\partial \vec{A}}{\partial t} - \gamma \nabla V, \tag{2}$$

where $\vec{J}_{\mathrm{e}}$ denotes an impressed current density, μ the permeability, V the scalar electric potential and γ the electrical conductivity. The second term of the right-hand side of equation (2) represents the induced eddy current density in an electrically conductive body at rest, which is placed in a time-varying magnetic field. The third term of equation (2) expresses the current density due to the potential difference in a conductor.

2.2 Mechanical field in a solid

In the case of linear elasticity and isotropic material data, the dynamic behavior of mechanical systems can be described by the following partial differential equation [3]

$$\frac{E}{2(1+\nu)} \left((\nabla \cdot \nabla)\vec{d} + \frac{1}{1-2\nu} \nabla(\nabla \cdot \vec{d}) \right) + \vec{f}_{\mathrm{V}} = \rho \frac{\partial^2 \vec{d}}{\partial t^2}. \tag{3}$$

In equation (3), E denotes the modulus of elasticity, ν the Poisson's ratio, ρ the density, $\vec{f}_{\mathrm{V}}$ the volume force and $\vec{d}$ the mechanical displacement.

2.3 Acoustic field in a fluid

The propagation of an acoustic wave in a homogeneous non-viscous fluid medium is governed by the linear wave equation [4]

$$\nabla^2 p = \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2}, \tag{4}$$

where p is the acoustic pressure and c the sound velocity in the fluid. The scalar velocity potential ψ, given by

$$p = \rho_{\mathrm{f}} \frac{\partial \psi}{\partial t}, \tag{5}$$

with ρ_{f} denoting the density of the fluid, obviously satisfies the same equation

$$\nabla^2 \psi = \frac{1}{c^2} \frac{\partial^2 \psi}{\partial t^2}. \tag{6}$$

In order to obtain a full description of the dynamic behavior of an electrodynamic loudspeaker, all coupling terms between the three physical fields have to be considered:

2.4 Coupling 'Electric Circuit - Magnetic Field'

Due to the fact that in most applications the electrodynamic loudspeaker is loaded by an electric voltage, the magnetic field equation has to be solved together with the electric circuit equation.

2.5 Coupling 'Magnetic Field - Mechanical Field'

In the case of a moving conductor in a magnetic field, the term

$$\gamma \vec{v} \times (\nabla \times \vec{A}) \tag{7}$$

has to be added to equation (2). This term represents the induced eddy current density in an electrically conductive body moving with velocity $\vec{v}$ in a magnetic field (motional emf). Here, the velocity $\vec{v}$ is given as the time derivative of the mechanical displacement $\vec{d}$

$$\vec{v} = \frac{\partial \vec{d}}{\partial t}. \tag{8}$$

A further coupling between the mechanical and the magnetic field is due to the magnetic volume force $\vec{f}_{\mathrm{V}}$ resulting from the interaction between the magnetic field and the total electric currents in the conductive parts of the moving coil system. This volume force can be computed by

$$\vec{f}_{\mathrm{V}} = \left(\vec{J}_{\mathrm{e}} - \gamma \frac{\partial \vec{A}}{\partial t} - \gamma \nabla V + \gamma \vec{v} \times (\nabla \times \vec{A}) \right) \times (\nabla \times \vec{A}), \tag{9}$$

where $\vec{J}$ denotes the total electric current density.

2.6 Fluid-Solid interaction

In the case of a fluid-solid interaction, continuity requires that the normal component of the particle velocity $\partial\psi/\partial n$ of the fluid must equal the normal component of the surface velocity v_{n} of the solid at the interface. Thus, the following coupling condition at a fluid-solid interface is derived

$$v_{\mathrm{n}} = \vec{n} \cdot \left(\frac{\partial \vec{d}}{\partial t} \right) = -\vec{n} \cdot \nabla \psi = -\frac{\partial \psi}{\partial n}. \tag{10}$$

In Fig. 2 all considered fields as well as their couplings are summarized.

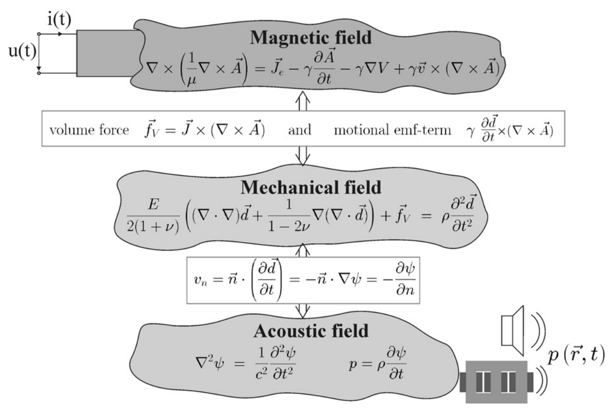

Figure 2: Considered fields and their couplings of magnetomechanical actuators

3 Finite Element Models

In this paper, the equations governing the electromagnetic, mechanical and acoustic field quantities including their couplings are solved using a finite element method (FEM). The theory of the underlying finite element scheme has already been reported in [5, 6] and will not be repeated here. This scheme has been updated with respect to the **modeling of a voltage loaded moving coil** to allow the **efficient and precise** simulation of electrodynamic loudspeakers:

- For the computation of the small-signal behavior of the electrodynamic loudspeaker the voltage-loaded moving coil is modeled by the very efficient *Motional EMF-term method* [7, 8]. This scheme, however, is limited by the assumption, that the loudspeaker has to be operated within the jump-out excursion, where the voice coil begins to leave the magnet gap. In this case the length of the voice coil wire immersed in the gap field is constant and, therefore, re-meshing of the simulation area is not required.
- Meanwhile, this scheme for the voltage loaded moving coil has been extended with respect to the modeling of the large-signal behavior of electrodynamic loudspeakers, where the voice coil leaves the homogeneous magnetic field of the permanent magnet. Therefore, to take account of the variation of average flux-linked turns (or force-factor Bl) for a coil under large excursions, a so-called *Moving Material method* has been applied. Since after each time-step, only the material data of the voice coil is updated no mesh distortion is caused. Therewith, no re-meshing of the calculation domain has to be performed.

Apart from this new coil modeling scheme based on the *Moving Material method*, which is required to take the magnetic nonlinearities into consideration, mechanical nonlinearities, i.e. geometric nonlinearities caused by large displacements and material nonlinearities due to nonlinear strain-stress relationships, have also been developed.

3.1 Small-signal computer model

In finite element methods, the region under consideration is subdivided into small discrete elements, the so-called finite elements. The finite element discretization of the electrodynamic loudspeaker under small-signal conditions is shown in Fig. 3. Here, the voice coil is discretized by so-called magnetomechanical coil elements based on the *Motional EMF-term method*, which solve the equations governing the electromagnetic and mechanical field quantities and take account of the full coupling between these fields. Due to the concentration of the magnetic flux within the magnet assembly, the magnet structure and only a small ambient region have to be discretized by magnetic finite elements. Furthermore, the surround, spider, diaphragm and former are modeled by pure linear mechanical finite elements. Finally, the surrounding fluid region in front of the loudspeaker is discretized by acoustic finite elements. The fluid region is surrounded by infinite elements, which have to be located in the far field of the moving coil driver in order to work correctly. The input level of these simulations is 1 W referred to 4 Ω.

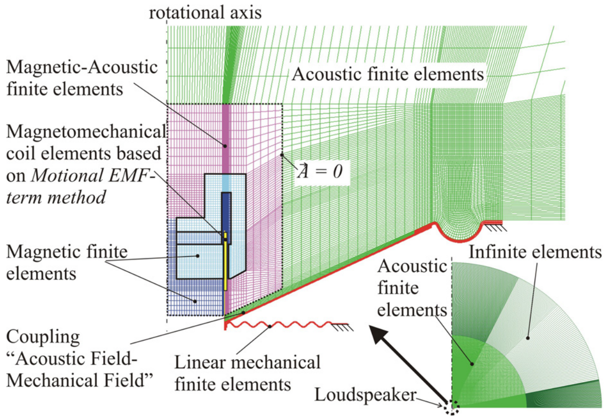

Figure 3: Small-signal finite element model of an electrodynamic loudspeaker.

3.2 Large-signal computer model

The finite element discretization of the electrodynamic loudspeaker under large-signal conditions is shown in Fig. 4. The following modifications have been performed in comparison to the above explained small-signal computer model:

1. To take account of the variation of the force-factor for a coil under large excursions (i.e. magnetic nonlinearities), the magnetomechanical coil elements discretizing the voice coil of the loudspeaker are based on the *Moving Material method*. In order to work correctly, the regions above and below of these elements have to be modeled by special magnetic finite elements.
2. Furthermore, first simulation results showed that the mechanical nonlinearities, i.e. the geometric nonlinearity as a result of large displacements and the material nonlinearity due to a nonlinear strain-stress relationship have only to be taken into consideration for the spider. Therefore, to allow a more efficient computation of the large-signal behavior the diaphragm and the surround are discretized by pure linear finite elements.
3. Finally, measurements have shown that the distortion factors of the near field and diaphragm acceleration are in excellent agreement. Due to this correlation a modified axisymmetric finite element model has been applied, in which acoustic elements were eliminated completely (see Fig. 4). The influence of the surrounding air, which consists of mass-loading effects and damping due to the sound emission, is now realized by so-called spring-elements. These elements have been located on the outside boundary of the surround and diaphragm. Therewith, it is possible to calculate the distortion factors of the electrodynamic loudspeaker very efficiently.

4 Verification

The verification of the computer models described above has been performed by comparing simulation results

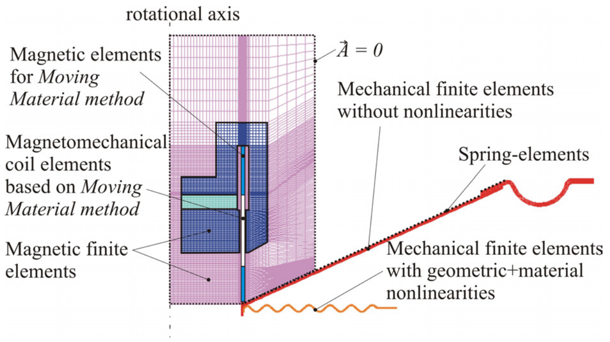

Figure 4: Large-signal finite element model of an electrodynamic loudspeaker.

with corresponding measured data. In a first step, the most important small-signal results (frequency dependencies of the electrical input impedance, diaphragm acceleration and axial sound pressure levels as well as Thiele-Small parameters) were considered. As can be seen in Fig. 5, good agreement between simulation results and measured data was achieved. Therefore, this good agreement shows the validity of the small-signal model depicted in Fig. 3.

Next, the force-displacement characteristics were measured and compared with simulations. Again good agreement between simulation and measurement was observed (see Fig. 6a). After this basic validation of the large-signal computer model, the harmonic distortion factors of the voice coil currents and diaphragm accelerations at large-signal conditions have been calculated. The input level of these simulations was 32 W referred to 4 Ω. As can be seen in Fig. 6b, the good agreement of measured and simulated results over a wide frequency and excursion range validates the large-signal model depicted in Fig. 4.

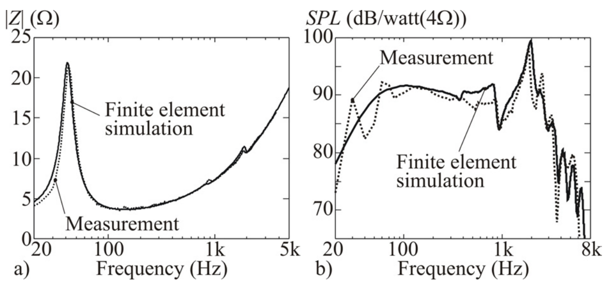

Figure 5: Comparison of simulated and measured small-signal results: a) Frequency dependency of electrical input impedance Z, b) Axial small-signal pressure response SPL at 1 m.

5 Application

To demonstrate the practical applicability of the developed simulation scheme in an industrial computer-aided design process, a low-frequency loudspeaker as used in the automotive applications was numerically analyzed and optimized with respect to the distortion factors under large-signal conditions.

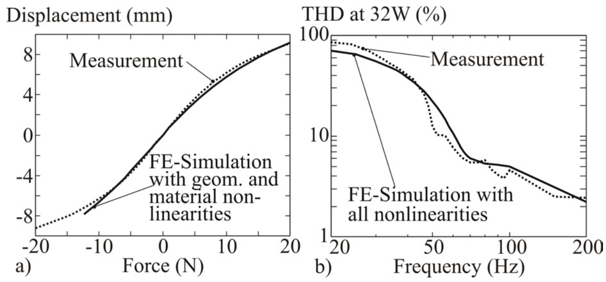

Figure 6: Comparison of simulated and measured large-signal results: a) Force-Displacement characteristic of the loudspeaker, b) Total Harmonic Distortion (THD) of diaphragm acceleration at an input power of 32 W.

5.1 Numerical analysis of the nonlinear loudspeaker behavior

Measurements as well as simulation results revealed that at frequencies $f < 60$ Hz the odd order harmonics and at higher frequencies the even order harmonics are dominated. The large advantage of the computer modeling is the separation of the different nonlinearities for the different components of the loudspeaker. In this way, the influence of the different nonlinear effects on the loudspeaker behavior can be very usefully extracted and researched in the simulation. For example, simulations showed that the magnetic nonlinearities cause notably quadratic distortion factors at frequencies $f > 60$ Hz, whereas the mechanical nonlinearities cause the rapidly increase of the even order harmonics in the lower frequency range (see Fig. 7). Furthermore, both mechanical and magnetic nonlinearities are responsible for the cubic distortion factor.

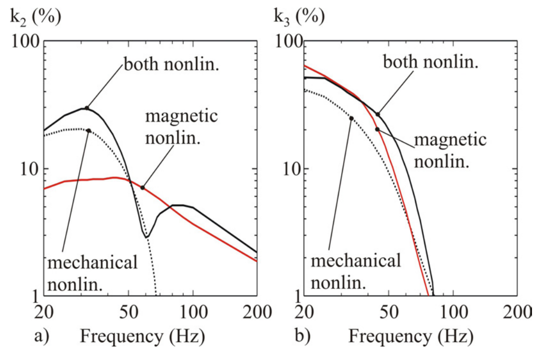

Figure 7: Numerical investigation of distortion factors of diaphragm acceleration at an input power of 32 W: a) Quadratic distortion factor k_2, b) Cubic distortion factor k_3

In a next step of the numerical analysis, the influence of design-parameters of the magnet system on the distortion factors has been investigated. Simulations considering only magnetic nonlinearities revealed that large coil flux variations result in notably odd order harmonics. On the other hand, an unsymmetric magnetic field in the air gap causes large coil offsets resulting in notably even order harmonics. Further computations showed that the position of the permanent magnet has a big influence on the symmetry of the magnetic field in the air gap and, therefore, can be used in the optimization of the system (see Fig. 8b).

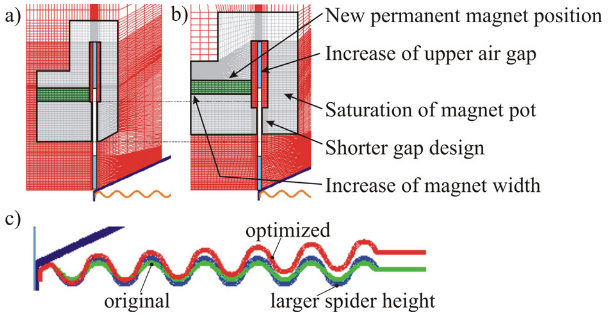

Figure 8: Finite element models: a) Original magnet system, b) Optimized magnet system, c) Original and optimized spider.

Furtheron, it could be shown, that the transient magnetic field of the current-carrying voice coil must not be neglected at large-signal conditions. To reduce the influence of the coil field under large-signal conditions on the symmetry of the force-factor, the whole magnet pot has to be saturated as well as the upper air gap above of the pole plate has to be increased (see Fig. 8b). These design-modifications result in a much more symmetric decrease of the force-factor (see Fig. 9a). Furthermore, to minimize the variation of force-factor, i.e. to raise the so-called jump-out excursion, the thickness of the pole plate has to be reduced (see Fig. 8b and Fig. 9a). Finally, since this design-modification results in a smaller efficiency of the loudspeaker, the width of the permanent magnet has to be increased.

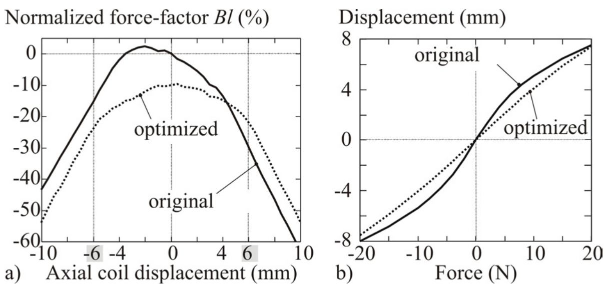

Figure 9: Comparison of the original and optimized loudspeaker: a) Simulated coil flux variation (normalized to the original small-signal value), b) Simulated force-displacement characteristic.

After the above explained numerical analysis of magnetic nonlinearities, the influence of design-parameters of the spider on the distortion factors caused by the mechanical nonlinearities has been investigated. Simulations considering magnetic and mechanical nonlinearities showed that a larger spider height results in a more linear force-displacement characteristic and significant smaller odd order harmonics (see Fig. 8c and Fig. 9b). Furthermore, a continuous displacement of each midpoints of the spider grooves causes a more symmetric force-displacement characteristic resulting in smaller even order harmonics

6 Conclusion

A numerical scheme based on a finite element method has been applied for the precise and efficient computer modeling of the complex dynamic behavior of electrodynamic loudspeakers. This method not only covers the simulation of the small-signal behavior but also the calculation of the large-signal behavior taking into account all magnetic and structural nonlinearities. The usability of the implemented calculation scheme has been demonstrated on a low-frequency cone loudspeaker as used in the automotive applications. The good agreement of measured and simulated results shows the validity of the presented method. Furthermore, the practical applicability of the developed simulation scheme in an industrial computer-aided design process has been proven by the numerical investigation and optimization of the large-signal behavior. The predicted reduction of distortion factors could be successfully confirmed by measurements on a new prototype. Consequently, the here presented computer tool provides a basis for more efficient development of electrodynamic loudspeakers, since both development time and costs can be reduced tremendously.

References

[1] NACS, **N**umerical **A**nalysis of **C**oupled **S**ystems, www.simetris.de

[2] P. S. Silvester, R. L. Ferrari, "Finite elements for electrical engineers", 3. Cambridge University Press (1996)

[3] F. Ziegler, "Mechanics of Solids and Fluids", Springer-Verlag, Vienna (1991)

[4] G. S. Kino, "Acoustic Waves: Devices, Imaging, and Analog Signal Processing.", Prentice-Hall (1987)

[5] M. Kaltenbacher, H. Landes, R. Lerch, "An Efficient Calculation Scheme for the Numerical Simulation of Coupled Magnetomechanical Systems", *IEEE Transactions on Magnetics 33*, no. 2, 1646-1649 (1997)

[6] R. Lerch, M. Kaltenbacher, H. Landes, M. Rausch, P.-C. Eccardt, "Combination of Finite Element and Boundary Element Methods in Computational Acoustics and Coupled Field Problems of Electro-Acoustic Transducers", Editor: von Estorff, Computational Mechanics Publication (2000)

[7] M. Kaltenbacher, M. Rausch, H. Landes, R. Lerch, "Numerical Modelling of Electrodynamic Loudspeakers", *COMPEL 18*, no. 3, 504-514 (1999)

[8] M. Rausch, R. Lerch, M. Kaltenbacher, H. Landes, G. Krump, L. Kreitmeier, "Optimization of Electrodynamic Loudspeaker-Design Parameters by using a Numerical Calculation Scheme", *Acta Acustica 85*, no. 3, 412-419 (1999)

[9] G. Krump, "Concerning the perception of low-frequency distortions", *Fortschritte der Akustik DAGA 2000*, Oldenburg, 486-488 (2000)