Audio Engineering Society

Convention e-Brief

Presented at the 136th Convention
2014 April 26–29 Berlin, Germany

Multiphysical Simulation Methods for Loudspeakers - A (Never-)Ending Story?

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ABSTRACT

Multiphysical simulations of loudspeakers are being investigated by scientific and industrial researchers for more than 40 years. At a first glance an electrodynamic loudspeaker seems to be a fairly simple assembly - a simple (sub-)system compared to typical applications of modern CAE methods. So where is the challenge? - in detail! Besides strongly coupled different physical domains (electromagnetics, mechanics, acoustics, thermal transport, fluid dynamics ...), we also have to deal with path dependent dynamic effects and nonlinearities (including instabilities) in each domain. Additionally, materials with totally different behavior (and thus totally different material models to be used) and different joining techniques for each component are used as well. This paper will summarize challenges for realistic simulations, and will discuss efficient solutions for daily usage in the industrial work flow of product development.

1. INTRODUCTION

The audio industry, as well as most industries today, is challenged by the need to (constantly) increase engineering efficiency. Computer Aided Engineering (CAE) based on simulation and analysis of the functional performance of products plays already a key role for more than two decades. CAE methodologies are today typically used at every stage of the development cycle, from first concept studies up to detailed engineering for final product development to be released to the market place (including modeling of the manufacturing processes as well). During the last years a strong trend for moving CAE upfront in the design process (to be applied already in the concept phase) can be monitored. Thus the term frontloaded Virtual Product Development (VPD) is often used. The advantages for moving CAE upfront are:

- more freedom in the design decisions

- design changes can be made at lower costs

These advantages additionally fulfill the above mentioned basic requirements to increase engineering efficiency (similar thoughts applied to the automotive industry can be read in [1]).

This frontloaded approach was first (successfully) introduced for the development of automotive and aerospace key components at the OEMs. A good example for a first application of VPD is the development of car body structures with respect to crashworthiness, fatigue or NVH behavior. Today it is stringent for almost all industries to follow the path of a frontloaded VPD cycle as well.

This paper is the first out of a planned series of publications on advanced modeling strategies for realistic simulation of loudspeakers. Within the context of this first paper a more general overview of the topic is given covering major challenges and its solutions. Further papers will go more into detail of each subtopic (i.e. physics involved) and special effects like due to nonlinearities.

This paper starts with a description of the basic theory of modeling the multiphysical behavior of electrodynamic loudspeakers by means of finite and boundary elements. A typical industrial example will demonstrate the power of this modeling strategy in efficiency especially in terms of accuracy. Finally the numerical procedures used for each major physical domain (i.e. electromagnetics, structural dynamics and acoustics) for linear systems will be discussed.

2. THEORY OF MULTIPHYSICAL MODELING OF LOUDSPEAKERS

There is a long tradition to treat loudspeakers as a multiphysical device. Already in the early 1970s several technical papers were presented to the AES [2] that resulted in a model which is based on the so-called "Thiele-Small Parameters". A.N. Thiele and R.H. Small developed a set of parameters and one-dimensional equations defining the relationship between a loudspeaker, a particular enclosure and the radiation of sound waves. Over time there have been a lot of developments to extend these early lumped parameter models to more sophisticated models with improved accuracy. Especially the recent work of W. Klippel on the large signal behavior (i.e. the nonlinear behavior of the loudspeaker) should be mentioned here [3].

However, all these lumped parameters models have one significant drawback; they are based on one-dimensional, scalar equations to describe a physical domain. Whereas the usage of a lumped parameter model for voice coil electromagnetics turned out to be very useful, for the mechanical domain and for the acoustical domain one can see a lot of limitations. E.g. the mechanical system is described in a lumped parameter model by a set of scalar values of stiffness, mass and damping. This leads to the fact, that this model is only capable of describing the pistonic motion of a loudspeaker's vibration system. This will yield to significant limitations in the frequency range where the lumped parameter model is applicable. At higher frequencies the motion pattern is not pistonic anymore and a multidimensional approach is necessary to model this behavior.

This fact has led to the development of models based on matrix methods. A fully coupled electrical-mechanical-acoustical simulation model for loudspeakers is now presented, which uses a lumped parameter model for voice coil electromagnetics, a finite element model for the mechanical domain and a finite or boundary element model for the acoustical domain.

2.1. Voice Coil Electromagnetics

In the lumped parameter model for voice coil electromagnetics the electrical force f^e acting on the coil under the assumption of a constant voltage source U is defined as:

$$f^e = U\frac{Bl}{R+i\omega L} - \frac{(Bl)^2}{R+i\omega L}v^e = f^{e,L} + f^{e,EMF}$$

Whereas B is the flux density, l the length of the wire in B, R the DC resistance of the coil, L the inductance of the coil and v^e is the velocity of the moving coil. $f^{e,L}$ is the Lorentz force and $f^{e,EMF}$ is the back electromagnetic force.

2.2. Structural Dynamics

The governing equation for the mechanical vibrations in the frequency domain, discretized by means of finite elements, can be written as follows:

$$(K^m + i\omega D^m - \omega^2 M^m)u^m = f^m$$

At a first glance there seems to be only a little difference in the governing equations by matrix methods and by lumped parameter models. However, the big difference is the dimension of the system. In the finite element governing equation stiffness, mass and damping are being described via matrices. K^m is the stiffness matrix, D^m is the damping matrix and M^m is the mass matrix. Furthermore, u^m is the vector of displacements and f^m is the vector of mechanical forces exciting the system. ω is the angular frequency. Typically the dimension is of several of thousands degrees of freedom. In fact the governing equation is a system of equations describing the mechanical vibrations with respect to a detailed definition of the geometry (CAD model) discretized via finite elements. Thus it is possible to use these models for the whole audible frequency range which is typically from 20 Hz up to 20 kHz where a lot of non-pistonic and non-axisymmetric motion patterns occur, which can't be described via a one-dimensional lumped parameter model.

2.3. The Acoustical Domain

The principle of using matrices for describing a physical domain is also used for the acoustical domain where the Helmholtz equation is discretized by means of finite or boundary elements to describe the three-dimensional propagation of sound waves in the frequency domain:

$$B^a p^a = f^a$$

Here B^a is an acoustic coefficient matrix which defines the relationship between the vector of the sound pressure p^a and a vector including effects of incident sound waves f^a. Thus it is possible to describe the sound radiation with respect to a detailed definition of the geometry (CAD model) including reflectional as well as diffractional effects.

2.4. The Coupled Multiphysical System

If we now tie together all the governing equations of the different physical domains, electrical, mechanical and acoustical domain, we get the following coupled system of equations describing the multiphysics of an electroacoustical transducer in the frequency domain:

$$\begin{bmatrix} K^m + i\omega(D^m + D^e) - \omega^2 M^m & C^{ma} \\ C^{am} & B^a \end{bmatrix} \begin{Bmatrix} u^m \\ p^a \end{Bmatrix} = \begin{Bmatrix} f^{e,L} \\ f^a \end{Bmatrix}$$

C^{ma} and C^{am} are coupling matrices connecting the mechanical and acoustical domain. These coupling matrices arise from the assumption of continuity of the velocity and of the pressure in the mechanical as well as the acoustical domain in the direction normal to the coupling surface. D^e is an electromagnetic damping which has been derived from the back electromagnetic force. More details of this theory can be found in [4].

It must be mentioned here that the coupled model alone will not automatically lead to realistic simulations. Additionally, we need to accurately describe our material properties in the electrical and structural domain. Thus a key aspect here are material measurement procedures that are specifically designed to measure electrical and mechanical parameters as well. However, this is beyond the scope of the paper and details of measurement methods will be presented in future publications.

3. AN INDUSTRIAL EXAMPLE FOR A REALISTIC LOUDSPEAKER SIMULATION

While in a "real" product development process a "real" loudspeaker is typically being measured in an anechoic chamber, we do similar in the virtual world. An example of a typical woofer loudspeaker for the reproduction of low frequencies can be seen in Figure 1.

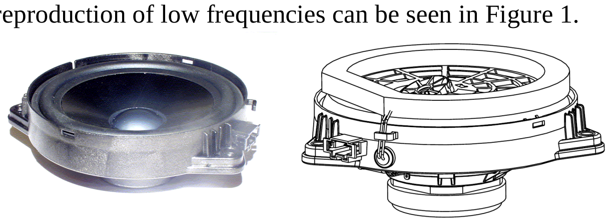

Figure 1 Real loudspeaker and CAD model

In Figure 2 a comparison of measured and simulated frequency response of the radiated sound pressure is given. The accuracy of the simulation based on the previously presented theory is within the manufacturing tolerances of the loudspeaker, and thus can be entitled as a realistic simulation.

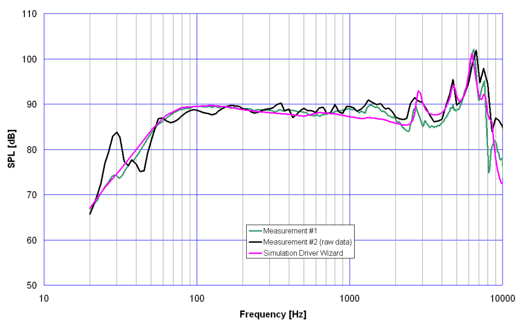

Figure 2 Comparison of measurement and simulation

4. MAJOR CHALLENGES IN EACH PHYSICAL DOMAIN

Actually the most important challenge is the strong coupling of all physical domains involved. Strong coupling within that context means that each physical domain interacts bidirectionally with other domains.

4.1. Electromagnetics

While typically the motor system can be treated as an axisymmetric device, and thus simplified 2D models can be applied for a majority of applications, its strong coupling to the structural domain (the loudspeaker's vibration system) via the voice coil acting in the magnet's air gap must be accounted for. For some motor structures also the variation of the flux field in axial direction is of crucial importance. Thus, typically finite element models for detailed motor design and optimization are being used.

At large excursions of the voice coil (when the loudspeaker is driven in the region of nominal power), a significant portion of the voice coil moves out of the main flux field, and thus less mechanical force is being induced. This nonlinear effect is very essential and causes unwanted distortion in the radiated sound. Additionally, voice coil inductance is also dependent on voice coil excursion and also on current. This leads to the need of nonlinear models to predict the loudspeaker behavior at large signals.

For system or subsystem level simulations (without the goal of designing a motor) 1D lumped models (additionally including nonlinearities to predict large signal behavior) as presented in chapter 2 are highly efficient.

4.2. Structural Dynamics

As discussed in chapter 2 the structural domain has to be modeled via finite elements to account for non-pistonic effects. The existence of circumferential bending waves can only be accounted for by 3D models. Thus 2D models have to be used with care. Additionally challenging are the thin-walled structures of cone and dust cap (and also surround and spider). By simply using 3D solid elements we would end up in a very large and unhandy model. Thus shell finite elements are typically being used to model the vibration system.

At large signals (and thus large excursions) major nonlinear effects arise from the material behavior and the change of the geometry, leading to a change in stiffness of the vibration system and thus generating distortion in sound radiation. Even if we would have a super-linear material, its change in geometric stiffness would lead to distortion. On top of this, due to the change in geometric stiffness instabilities may occur (snap-through and bifurcation), defining an additional source of heavy distortion.

4.3. Acoustical Domain

The major challenge here is the strong coupling to the structural domain. I.e. the movement of the loudspeaker's vibration system has an effect on the surrounding acoustic medium (air, sound waves are being generated) and the surrounding air has vice versa an effect on the movement of the structural domain (typically called added mass and stiffness effect).

However, for some applications, e.g. small transducers as used in mobile devices and horns for professional applications, viscous effects of the air have to be accounted for. Sound energy is being transformed to thermal energy (viscothermal effect) and heavily influences the radiated sound field – another source of nonlinearity.

5. OUTLOOK

Now it should be clear where the major challenges of realistic loudspeaker simulations are – a lot of important details that are part of the whole puzzle. The good news is, that for all challenges solutions are available. However, available not as a single software package but as a simulation process model developed by the author. More details of this process model will be published in future papers.

6. REFERENCES

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