New tools in room acoustic simulation

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ABSTRACT

For the room acoustic simulation a data base for absorption and scattering behaviour of the most different constructions, geometrical structures and materials is necessary. The absorption coefficient is often to be derived from test certificates or from the standard literature. In contrast, in the case of the scattering coefficient (Scattering after ISO 17497-1) this is less often the case. Therefore tools are in development which permit the frequency-dependent calculation of the absorption and the scattering coefficient for the geometrical acoustics, however, also the calculation of complex reflection factors or wall impedances for the wave acoustics. Additionally sound insulating measures are predicted ("AFMG SoundFlow" and "AFMG Reflex"). These tools are explained as a data base supplier for the FEM-based mode simulation in small rooms including the calculation of complex transfer functions at low frequencies.

1. INTRODUCTION

1.1. Motivation and Overview

Over the last two decades the modeling of sound reinforcement systems and room acoustics in large and medium-size venues such as stadia, concert halls or railway stations has developed into an elementary and widely practiced step of the design process. Nowadays acoustic modeling is considered as a standard among professionals in the audio industry because it can greatly reduce the cost and time involved in a design project. Unfortunately, the available tools represented by commercial simulation software are generally limited:

- Use of new wall and ceiling materials with unfortunately unknown acoustic absorption data
- No information about the scattering behavior about all structured surfaces
- Limitations of the frequency range to mid and high frequencies.

So we had the following motivation to create a tool called AFMG SoundFlow:

- Prediction of Impedance data for LF simulations
- Prediction of Absorption data for HF simulations
- Creation of tools for Building Acoustics
  - Sound Transmission Class (STC) acc. EN 12354
  - Noise Reduction Coefficient (NRC)

In the same way the forecast of scattering values is needed, which in most of the cases cannot found in text books. So by means of the software tool AFMG Reflex this prediction comes close to real values.

Beside tools to predict the absorption and scattering behavior of wall structures new methods are needed to calculate the radiation behavior at low frequencies.

The mathematical and numerical algorithms, such as ray tracing, are only valid in the frequency range where the wave length is small compared to the characteristic dimensions of the structure and of objects in the room.

The dividing line can be roughly identified with the so-called Schroeder frequency, which defines a specific frequency for each room that represents the transition from clearly distinguishable room modes in the low frequencies to strongly overlapping modes in the high frequencies, and thus from modal behavior to a statistical, diffuse field. While FEM and other wave-based modeling tools are available since several years, they are all of largely academic nature and do not fit the modeling requirements of practical projects and designs, with respect to input and output data, performance, memory requirements and ease of use. We will be using a newly developed tool set and perform the FEM analysis in the following steps:

Generating a volume and surface mesh based on given geometry data,

Assigning acoustic material data to each surface, in particular defining the complex input impedance, by using the SoundFlow tool

Computing the room modes,

Defining loudspeaker locations and levels,

Calculating transfer functions for any receive location,

Displaying results as 3D mappings or transfer function and impulse response plots,

Combining low-frequency results with high-frequency simulation results in order to obtain a broadband frequency response for analysis and auralisation purposes.

Based on this approach, we will present a case study. It is concerned with a small studio room that is characterized by its reverberation time, geometry, volume and acoustic design. Using the new simulation tool a mesh is generated for that room. After that, modes and transfer functions are computed. Typical acoustic characteristics are evaluated and special properties of the rooms are highlighted.

After that the modeling results are compared with measurement results of the same space. The modal distribution is calculated at different spots as well as the room transfer function for a source-receiver location. It is shown that the modeling results match well with measurements within given uncertainties.

1.2. Modal and Diffuse Field

Frequency analysis of the steady-state sound field of a room leads in most cases to a clear separation between low-frequency behavior and high-frequency behavior. One of the most common criteria for the location of this dividing line is the spectral density of room modes. In the low-frequency domain, individual modes can be clearly identified and isolated. Here one speaks of the so-called modal sound field. In the high-frequency domain, room modes overlap so much that they cannot be distinguished anymore and establish a so-called diffuse sound field. The approximate transition frequency is given by the Schroeder frequency [1]:

(1)

where T is the reverberation time (RT_{60}) and V is the room volume. For traditional studio rooms of volumes of the order of 30 to 60 m^3 and reverberation times of about 0.2 s up to 1 s the Schroeder frequency is in the range of 100 to 400 Hz.

While the Schroeder frequency can be only a rough indicator and is argued about occasionally (e.g. [2]), it provides a good rule of thumb for estimating the lower frequency limit of simulation results performed with high-frequency analysis methods. Around and below this boundary a wave-based modeling method such as FEM is required instead of a ray- or particle-based method.

2. PREDICTION OF ABSORPTION AND SCATTERING COEFFICIENTS AND OTHER ACOUSTIC PARAMETERS

2.1.1. Tool AFMG SoundFlow

The new tool assumes wall structures of different layers and allows calculating the following acoustic parameters of course frequency-dependent [3]:

- Absorption Coefficient
- Reflection Coefficient
- Transmission Loss
- Input Impedance
- Reflection Factor
- Transmission Factor

This may be done for different directions of sound incidence: Diffuse one and unidirectional (angle-dependent). Figure 1 illustrates the way to do calculations for multi-layer structures.

Fig. 1: Multi-layer structure

The Calculation is done in the following steps:

- Impedance describes the acoustic properties: $Z = p_0/v_0$
- Calculation of transmission: $\tau = |p_N/p_0|^2$
- Boundary conditions for back size of the wall construction:
  - Rigid wall: Sound pressure $p_N = 1$ and Sound velocity $v_N = 0$
  - Air: Sound pressure $p_N = 1$ and Sound velocity $v_N = 1/Z_{Air}$
- Multi-layer structures are calculated layer by layer: $(p_N, v_N) \rightarrow (p_{N-1}, v_{N-1})$
  - Different computational models can be applied to each layer

The next figure 2 shows a multi-layer structure of a thin microperforated foil in front of a rigid wall with 200mm air space

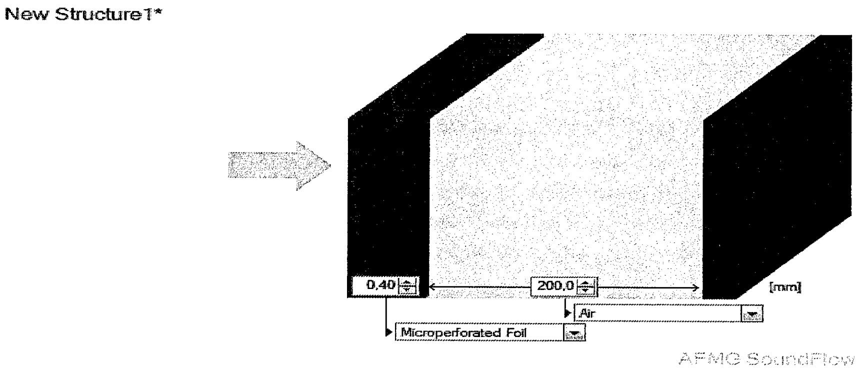

Figure 2: Sample structure

A comparison between measurement [4] and prediction results for the diffuse sound incident is shown in the next figure 3.

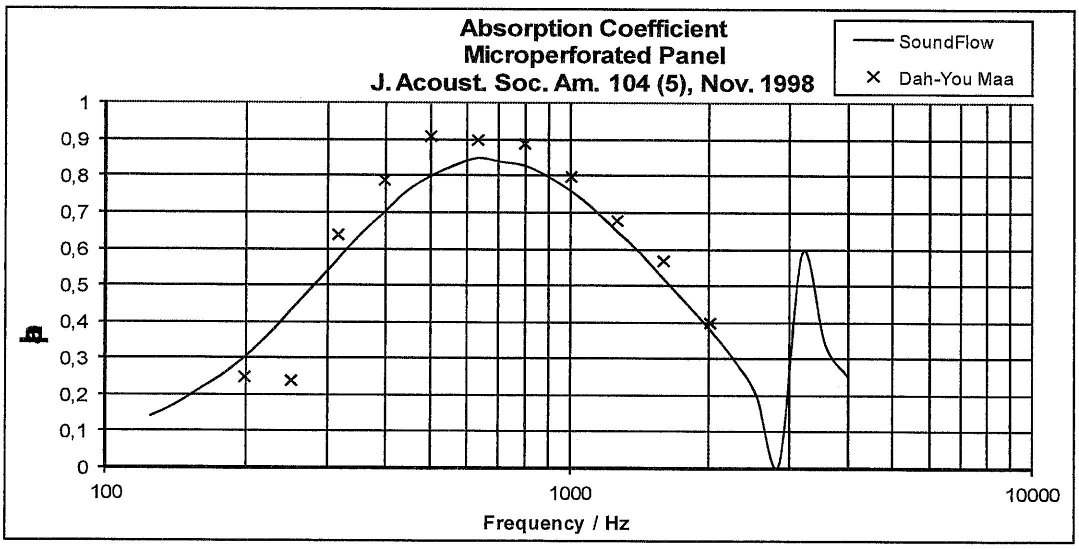

Figure 3: Comparison between measured und calculated results of the absorption coefficient

Another example illustrates the results to predict the transmission loss of multi-layer structure, see fig. 4

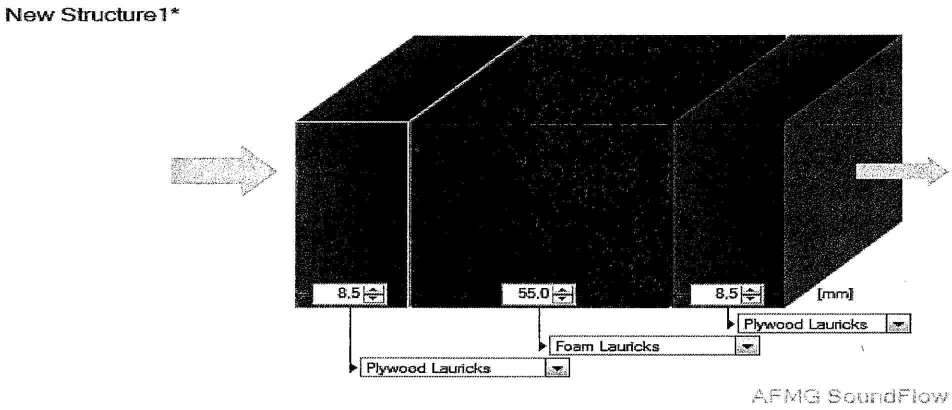

Fig. 4: Multi-layer structure of plywood and foam

The next figure 5 shows the comparison between measured (by Lauricks et al [5]) and predicted results of the transmission loss.

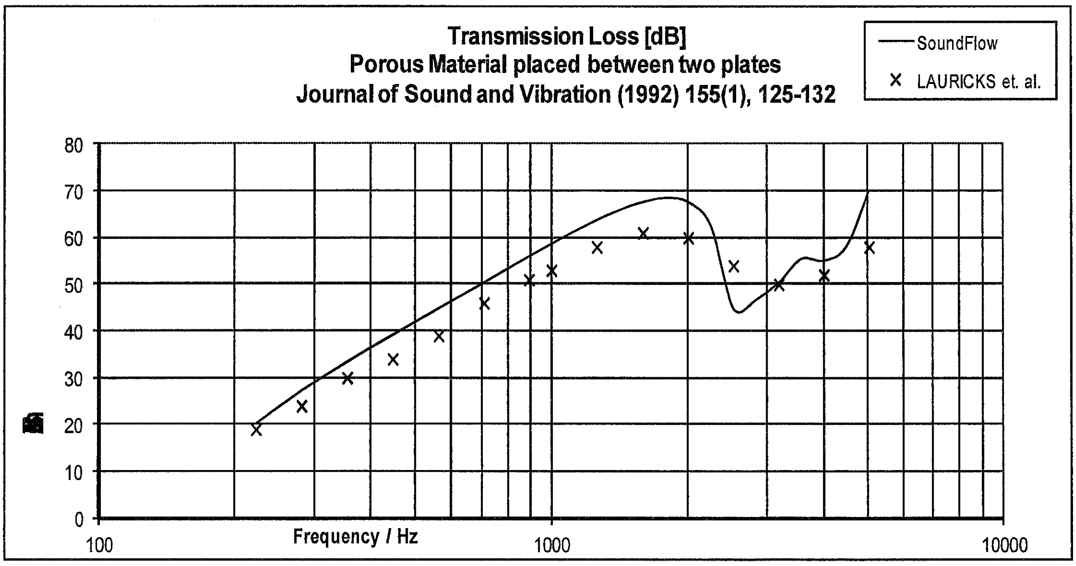

Fig. 5: Transmission loss: Comparison between measured data and predicted data

Significant research was performed in the field of modeling wall structures with regard to sound reflection and transmission, e.g. [6]. Based on this research SoundFlow allows to edit for all layers of wall structures specific data, like:

- Density in kg/m^3
- Young's Modulus of elasticity in GPa
- Poisson's Ratio (Strain factor)
- Bending Loss factor
- Flow Resistivity in $kPa \cdot s/m^2$

This way new materials may be used in the software.

2.1.2. Tool AFMG Reflex

By solving differential equations on the boundary of a domain (BEM) the following results may be achieved by using Reflex [7]:

- solving scattering problems
- coupling to FEM to solve semi-open rooms
- Advantages of BEM:
  - Works fast and exact for "small" structures
  - Can be used for open spaces
- Disadvantages:
  - Scales with higher order as FEM: longer calculation time

The calculation of Sound Scattering by a Structured Surface using BEM happens as shown in figure 6.

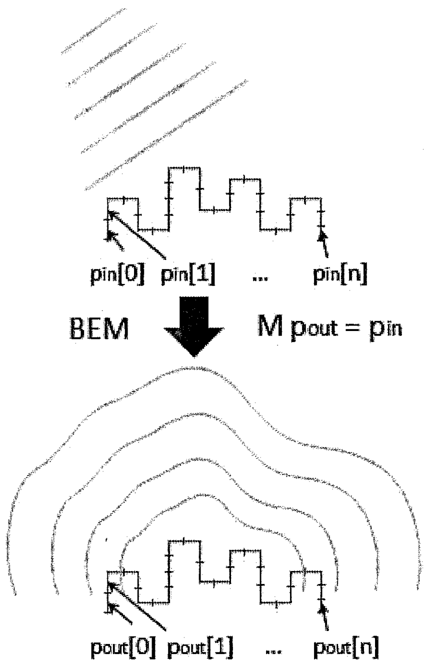

Fig. 6: BEM calculation on structures

The Steps to calculate scattering coefficients are as follows:

- Creation of a Structured surface
- Tessellation into segments
- Incident plane wave
- Calculation of sound pressure at surface
- Solving the system of linear equations
- Calculation of the resulting sound pressure
  - Calculation of reflected wave front

In Postprocessing the scattering and the diffusion coefficient are calculated. The scattering coefficient is needed in prediction software like EASE, CATT or Odeon and is defined as

(2)

This scattering coefficient is a measure to quantify the scattering properties of wall or ceiling parts relative to the specular reflection. In contrast the diffusion coefficient describes the scattering properties in a more qualitative way, the higher the value the more the sound is scattered homogeneously in all room directions.

The next figure 7 shows a reprint of the Reflex tool.

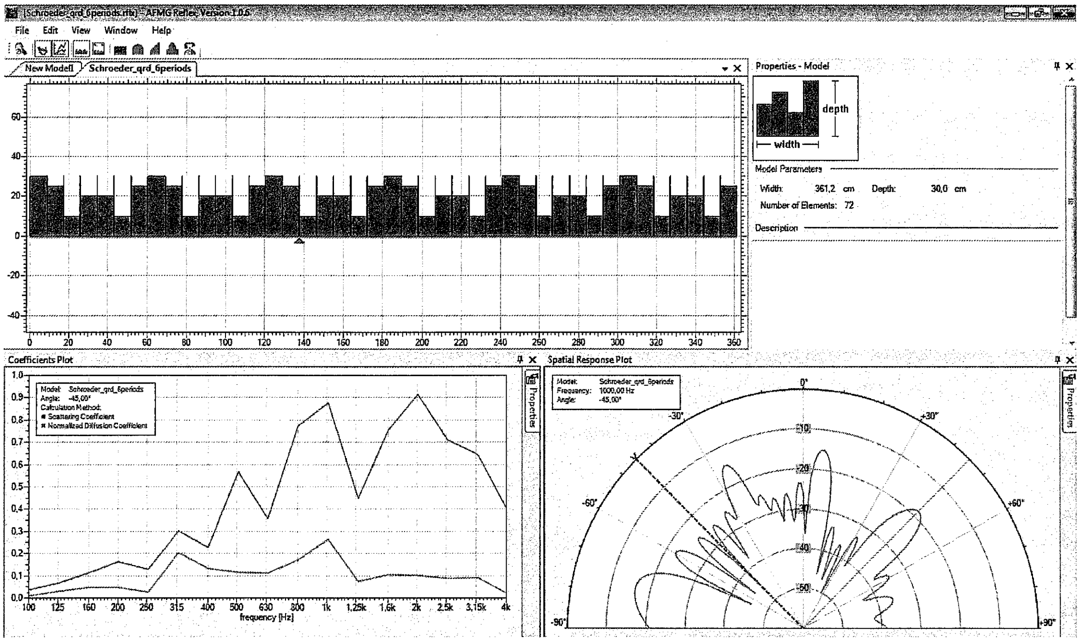

Fig. 7: Scattering behavior of a QRD Diffusor

3. HERE" MODELING WITH FEM

In this section we will give a brief overview of the functionality of the tools used and of the results they can provide. Simultaneously these elements represent the regular steps of performing an FEM analysis.

3.1. Room Model and Mesh

As a first step, a three-dimensional indoor room model has to be created. It normally consists of a number of discrete surfaces that form a closed boundary in 3D space. In practice, such models are derived either from CAD drawings, e.g. as produced by AutoCAD or SketchUp, or imported directly from 3D acoustic modeling software such as EASE [8] or CATT-Acoustic [9].

After that, the enclosed volume is converted into a volume mesh of either tetrahedral or hexagonal elements (Figure 8). Numerical difficulties may arise in this process if the underlying boundary surfaces are not plane or if their size is different by orders of magnitude.

The granularity of the mesh is determined by the desired target resolution, that is, by the frequency range of interest. The upper limit of that frequency range establishes a critical wavelength. Mesh elements should normally be smaller in any dimension than a defined fraction of the wavelength, such as 1/8. This corresponds to a trade-off of calculation accuracy vs. calculation performance, duration and memory required.

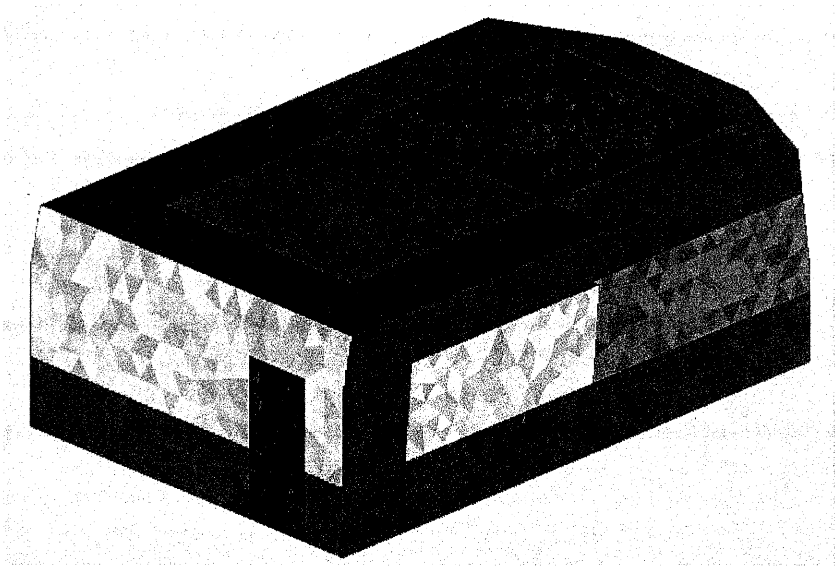

Figure 8 Tetrahedral mesh.

3.2. Boundary Conditions

Like in ray-based acoustic modeling, boundary conditions must be determined for the surface elements. But in contrast to the high-frequency domain where mostly only absorption data are used, this normally requires defining complex input impedance data for each surface node of the mesh. In practice, such data rarely exist for common building materials, unfortunately. One of the tools implementing this theoretical framework is AFMG SoundFlow (see chapter 2.1.1), which was used for the modeling of boundaries in this work (Figure 2).

3.3. Modal Characteristics

Once the mesh as well as the boundary conditions are given, the eigenmodes of the room can be calculated. Physically, these can be interpreted as the preferred vibration frequencies or resonance frequencies of the room (Figure 9). Any (linear) sound transmission within the room can be described by the linear combination of all modes and their degree of excitation.

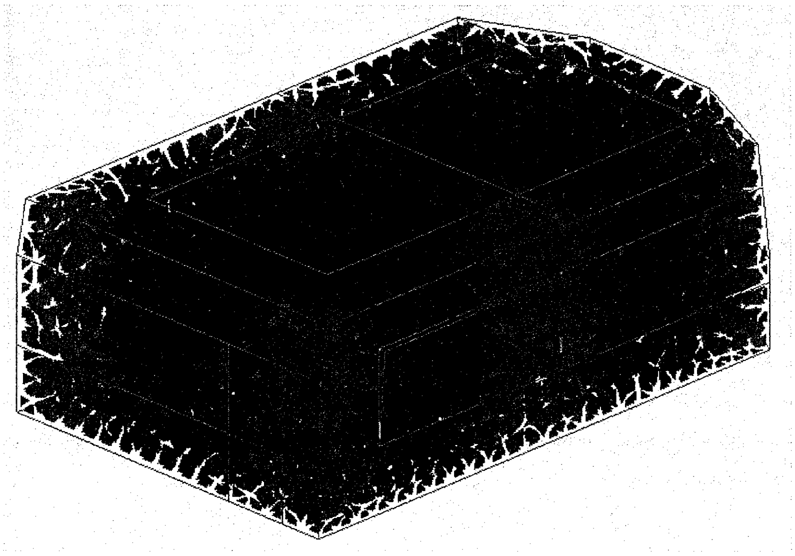

Figure 9 Room mode at 56 Hz, red colors indicate pressure extrema.

3.4. Transfer Function

Finally, for the detailed analysis of the sound system in the room, it is inevitable to define the location of sound sources. A transfer function can then be calculated for any point in the room as the frequency-depending solution of the linear system of equations.

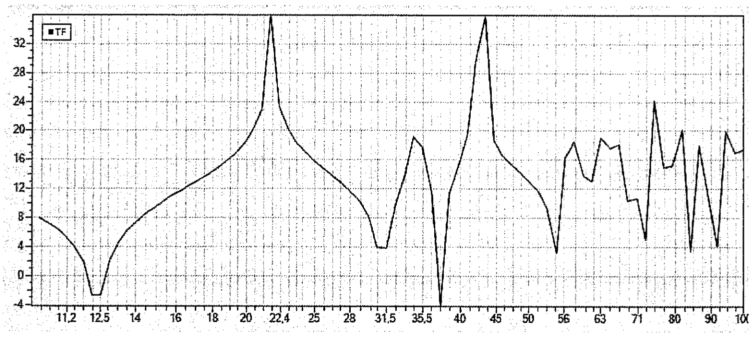

Figure 10 Simulated transfer function in the range from 10 to 100 Hz, shown as magnitude in dB over frequency in Hz.

4. CASE STUDY

4.1. Description

The used example studio room is a full structure, designed to provide sufficient sound isolation from the surrounding other rooms. Simple flat panel structures assure a flat reverberation response. With a volume of 49 m^3 and a reverberation time of 0.15 s the Schroeder frequency (1) of this studio room is about 110 Hz.

4.2. Model

For the FEM simulation a 3D model of the studio was created (Figure 11). From the model a mesh was generated that consisted of approximately 125,000 tetrahedrons (Figure 12). This allows for stable simulation results up to 120 Hz.

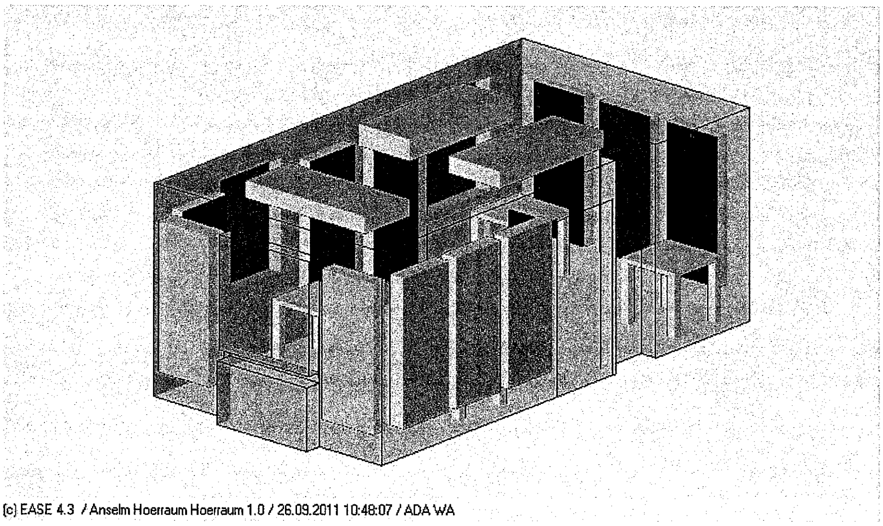

Figure 11 Studio – 3D model.

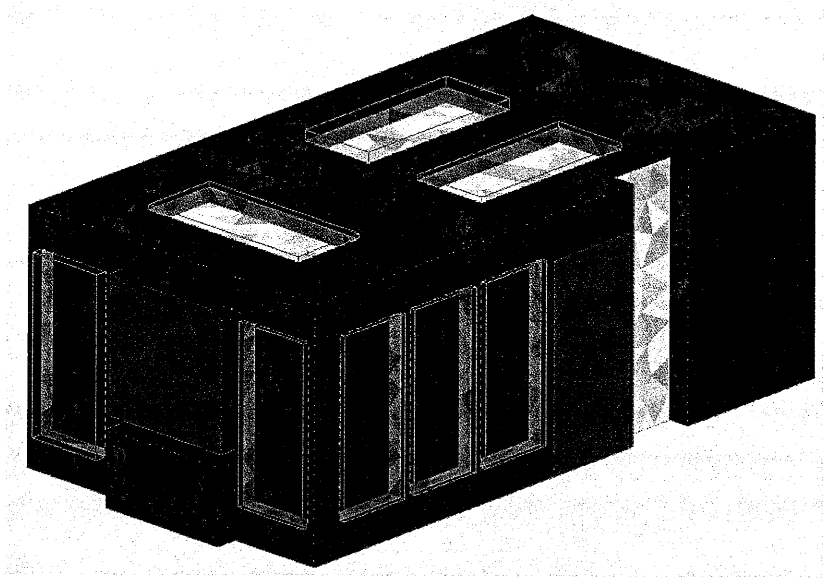

Figure 12 Studio – mesh.

Using an iterative eigenvalue solver we obtained the lowest eigenfrequencies and the corresponding pressure distributions for rigid boundary conditions (Figure 13).

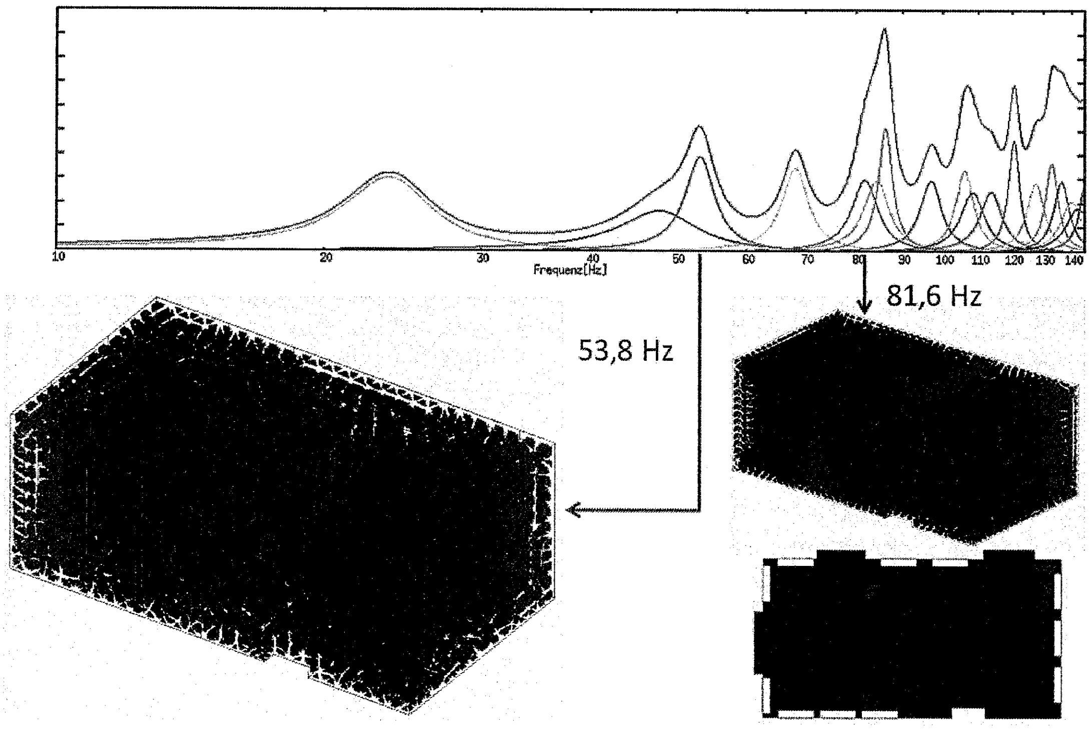

Figure 13: Undamped modes at 53,8 Hz, and 81,6 Hz; Red colors represent pressure extrema.

When non-rigid boundary conditions are assigned to the model, the eigenmodes are distorted in space and shifted towards lower frequencies. But even the undamped modes can be helpful in order to identify certain problems like dips in the transfer function or to optimize subwoofer placement.

5. COMPARISON WITH MEASUREMENT

For comparison of measurement and simulation all measured transfer functions (by using EASERA [10]) where simulated in the frequency range of 20 – 120 Hz using FEM.

Modes cause extreme values in the Transfer function. The sound pressure at the positions of the source and the receiver determine the actual influence of modes.

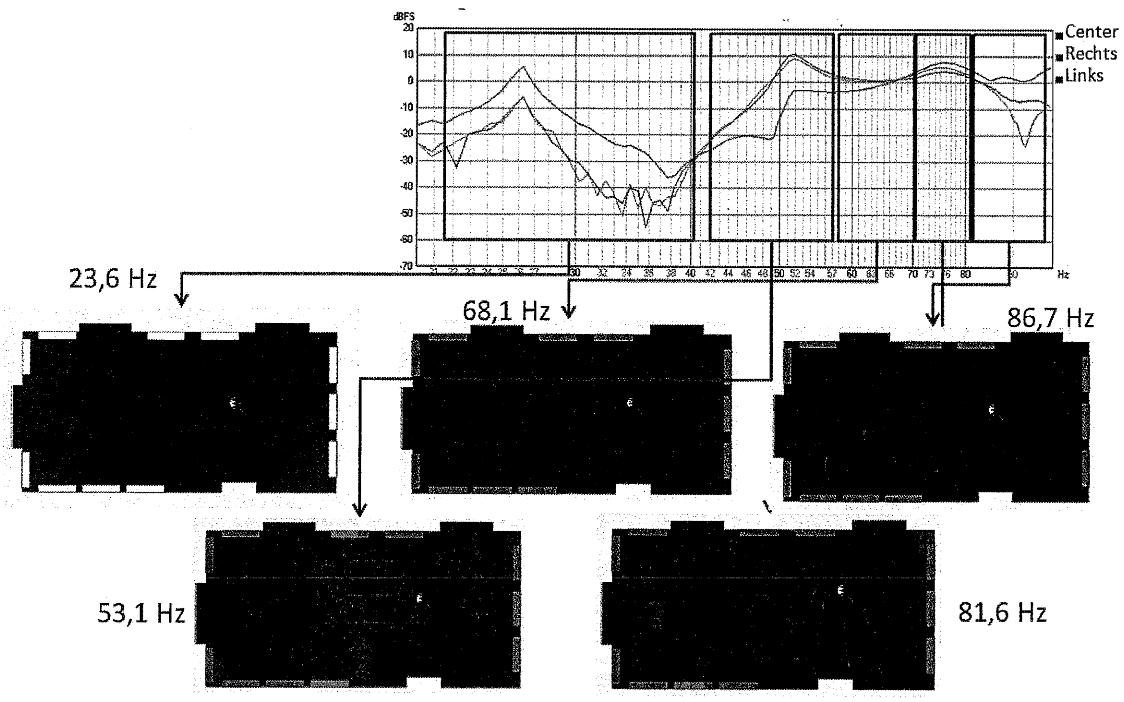

Figure 14 - Layout of modes in relation to speaker and listener positions

The comparison of measured and simulated transfer functions for the Center-Listener behavior is shown in the next figure 15.

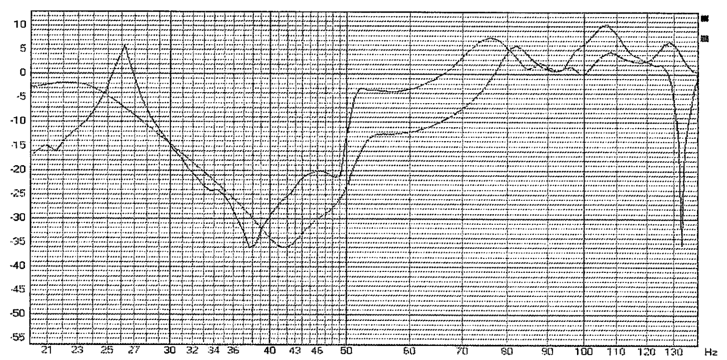

Figure 15 – Comparison between measured (green) and simulated TF curves (red)

The simulated transfer functions show a good match with the measured data. It can be seen that the characteristic shape of the transfer functions is very similar for the simulation and the measurement, see also [11].

6. HERE" CONCLUSIONS

Even with rough approximations of the boundary conditions (of course by using such tools like AFMG Reflex and AFMG SoundFlow) it is possible to qualitatively reproduce the measurement results using FEM simulations.

For further improvement, boundary conditions have to be modeled more accurately.

The influence of certain eigenmodes on the transfer function can clearly be seen. This can be helpful to identify problems like dips in the transfer function and to find optimal positions for absorbers and subwoofers.

It is planned to further improve the simulation algorithms and the studio model in order to obtain a better match with measured data. New case studies are currently being performed. Results will be presented in future articles.

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