



SIMULATION OF ROOM ACOUSTICS USING COMSOL MULTIPHYSICS

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Abstract. The modeling programs provide a wide range of possibilities for simulating acoustic systems. This paper describes programs used in acoustics for various purposes, such as Sound PLAN, AFMG SoundFlow, WinFLAG, Comsol multiphysics, ANSYS, Roomsim. For the purposes of the current research, the acoustic simulation of the room was carried out. Physical parameters as impedance, sound hard boundary and normal velocity were considered. The sound pressure level in rooms was investigated. Possibilities of using Comsol Multiphysics in the research of acoustics were investigated. Results of the current research show high-frequency eigenmodes located in the corners of the room and in the center of the room. Sound pressure level increased from low to medium frequency and then decreased with frequency drifts. At the frequency of 5000 Hz, minimum sound pressure is observed, which is associated with the decrease in the wavelength co-occurring with the decrease in frequency.

Keywords: sound pressure levels, impedance, Comsol Multiphysics, frequency, room acoustics.

Introduction

Noise is a serious environmental problem. According to the data from the EU Survey on Income and Living Conditions for the year 2015, 15.6% of Lithuanians declared they were affected either by noise from neighbours or from the street; 14.8% of Lithuanians declared they were affected by pollution, grime or other environmental problems (Directive E. U. 2002).

Modeling software allows evaluating the acoustic properties of environment. Considerable amount of research is devoted to such programs and their application in acoustics.

Modeling is also an important step in the development of the sound absorption plate in order to explore the porous structure. Models include specific geometric parameters: perforation diameter, hole spacing, panel thickness, and depth of back air cavities etc. (Song *et al.* 2016). Calculated parameters include absorption and reflection coefficients, transmission loss, input impedance, reflection factor and transmission factor.

Several methods of modeling room acoustics, e.g. finite element method (FEM) and boundary element method (BEM) were used in the attempt of solving the wave equation numerically (Siltanen *et al.* 2008).

The core programs for modeling in acoustics are Sound PLAN, AFMG, Sound Flow WinFLAG, Comsol multiphysics, ANSYS, Odeon, Roomsim.

Models of properties of acoustic waveguides are useful in many applications where acoustic waveguides are used. Rund describes a simple and useful tool implemented in Matlab which allows rapid analysis of transfer properties of an acoustic waveguide with certain shape and dimensions (Rund 2005).

Currently there is a variety of tools available to simulate the room acoustics of echoic environments such as the commercial architectural simulators Odeon or EASE. However, the focus of these software packages is on the naturalization and architectural analysis of geometrically complex rooms such as churches, concert halls, etc. This level of sophistication is not necessarily required for the analysis of three-dimensional audio techniques/algorithms or evaluation of microphone arrays in echoic environments. A room acoustics simulation tool which caters more for evaluating signal processing algorithms is the freely available shoebox room acoustic simulator developed by Schimmel *et al.* for MATLAB (Wabnitz *et al.* 2010).

The Roomsim program simulates the geometrical acoustics of a perfect rectangular parallelepiped room volume using the image source model to produce an impulse response from each omnidirectional primary source to a directional receiver system that may be a single sensor, a sensor pair or a simulated head. The Allen and Berkley algorithm has been extended to include frequency dependent sound absorption coefficients. Using this, the Roomsim program provides the ability to select different materials for each of the six major surfaces of the simulated room from a list of (at present) 20 standard building materials (plus 4 synthetics, including anechoic) (Campbell *et al.* 2005).

Sound PLAN utilizes the thermoviscous acoustic interface in a submodel to obtain detailed results for the transfer impedance of a perforated plate (including the thermal and viscous losses). The software programs allow to work with several configurations of the parameters. Similar configuration for both programs is required.

The impedance is in turn used as an internal impedance in a pressure acoustics model of a muffler. The results are compared to classic impedance models and measurements.

Noise levels can be calculated using the program Sound PLAN. A new method for urban road noise prediction based on the original source and propagation models has been proposed (Guo *et al.* 2013).

Acoustic modeling by AFMG Sound Flow. Various types of modeling software have proven to be valuable design tools for many aspects of acoustical design and noise control. Software packages are available to model design parameters such as environmental noise, exterior noise propagation, reverberation time, absorption coefficients and ratings such as sound transmission class (STC) and impact insulation class (IIC). Many types of auralizations can also be digitally created.

The calculation engine of AFMG SoundFlow is an accurate implementation based on the theory of sound absorbers developed by Mechel, Bies and others. Various computational models are available, including the calculations according to the ISO 12354 standard. All results can be exported as tables, graphs, complete reports and as EASE material files.

AFMG Sound Flow (hereafter referred to as SoundFlow) is a simulation program developed by Ahnert Feistel Media Group (AFMG) located in Berlin, Germany. AFMG is well known in the acoustical and audio-visual communities for other software packages, such as EASE, EASERA and SysTune. SoundFlow allows the user to construct a virtual assembly from a variety of absorbers,

perforated panels and plates (concrete, gypsum, plywood, etc.) (Ahnert 2011–2016). Calculated parameters include absorption and reflection coefficients, transmission loss, input impedance, reflection factor and transmission factor (Horan 2014).

Room acoustic modelling techniques and especially the room acoustic computer models have developed over the last decades (Rindel 2002) and highly accurate prediction models are available today. Although the room acoustic modelling technique has originally been devoted to the acoustic prediction and design of auditoria, the problems are equally challenging in work rooms, and to a great extent the same methods can be adopted (Rindel 2010).

The reciprocity principle is well-known and has many applications in acoustics and vibro-acoustics. This paper discusses a reciprocity measurement method to determine the radiation efficiency of a vibrating structure. An acoustic finite element model of the two plates has also been developed in order to provide a reference for the two types of measurement. Commercial software (Comsol Multiphysics) has been used (Squicciarini *et al.* 2015).

The main drawback of the latter and other inverse characterization procedures is the requirement of test samples, which increases product development costs in the early stages, thus limiting their popularity in the manufacturing industry of sound absorbing materials. In this context, complementary modeling and characterization techniques must be developed. The main aim of this work is to study some perforated plates backed by an air cavity using a finite element methodology (FEM). For this purpose, the thermo-acoustics interface included in the acoustics module of Comsol 4.3 b software is used (Pi *et al.* 2014).

The Comsol Multiphysics Group was founded by Mr. Svante Littmarck and Mr. Farhadin in Sweden, in 1986. The Comsol Multiphysics software has been widely used in various domains of science research and engineering calculations, for example, it was used in global numerical simulation. Following the major boost brought by computer technology, more and more computer software has been widely developed and used in the arena of engineering. The usage of software can help engineers to solve problems efficiently. Comsol Multiphysics is the software enabling the engineer to not only make drawings but also carry out physical analysis (Xiong 2010).

Finite Element Model used to analyse sound propagation in lined ducts was researched to determine the sound attenuation inside the lined duct. The Time-harmonic analysis model type has been used in Comsol Multiphysics. The numerical model was used to predict the

insertion loss inside rectangular lined ducts in a frequency range from 250 Hz to 4000 Hz.

A numerical finite element model of a perforated panel including these loss mechanisms was implemented. For this purpose, the linearized Navier-Stokes model included in the commercial package Comsol Multiphysics was used (Sakagami *et al.* 2006).

The program Comsol Multiphysics has been an effective simulation tool used to conduct numerical calculations of the sound propagation and absorption properties of materials in practical engineering.

Results of the related analyses show that ANSYS has been an effective simulation tool in numerical calculation of the sound propagation and absorption properties of materials in practical engineering. However, if the investigation is carried out at a fundamental level and deep access to the physics involved is required, time being secondary, it is preferable to use Comsol. The program is designed for scientific research; Comsol is oriented more towards the academia and provides a simple, easy to use interface. ANSYS is more industry oriented. Simulation by Win FLAG calculates the absorption coefficient, impedance, sound reduction index; this program has not got such a wide range of opportunities compared to Comsol and ANSYS. Sound PLAN is not to be used for scientific research, it is an industry oriented product. AFMG Sound Flow has limitations in the materials that can be used for modeling. AFMG Sound Flow does not have as much functions as Comsol and ANSYS.

Methodology

The main problem of the research is related to the propagation of a sound wave in the room. This can be solved using the module of pressure acoustics, frequency domain. The interface is designed for the analysis of various types of pressure acoustics problems in the frequency domain, all concerning pressure waves in a fluid. An acoustics model can be a part of a larger multiphysics model that describes, for example, the interactions between structures and acoustic waves.

In this study a room with the dimensions $5 \times 4 \times 2.6$ meters equipped with a flat-screen TV, a sideboard, two speakers, and a couch was modeled. To illustrate the effects on the music, a few resonance frequencies in the vicinity of different frequencies were computed.

When simulating acoustics, or any wave phenomenon in general, it is important to resolve the expected wavelength problem properly.

Using Comsol Multiphysics Comsol pressure acoustics, frequency domain (acpr) the problem can be solved in the following ways:

- a) Geometry modeling. According to the subject's shape and the condition of the question, a model (1D, 2D, or 3D) is established in Comsol. An example of room geometry is given in Figure 1.

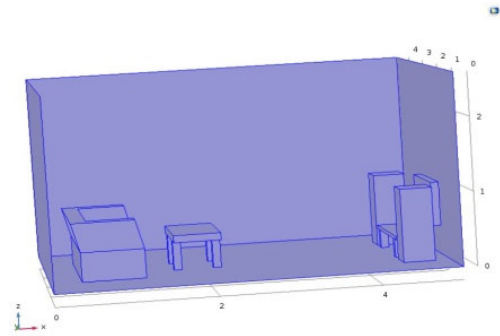


Fig. 1. Comsol 3 D model

- b) Physics modeling. Pressure Acoustics, boundary condition for a sound hard boundary or wall – it can set boundary conditions on the interface of different materials. It can also set boundary conditions on the interface between material and the environment. Normal Velocity node in time-harmonic analysis to specify the velocity component Impedance node adds an impedance boundary condition, which is a generalization of the sound-hard and sound-soft boundary conditions.
- c) Resulting sound pressure level.

The prediction that speakers placed in the corners of the room excite many eigenmodes and give a fuller and more neutral sound, however, holds for real-life rooms.

The Frequency Domain study and study step are used to compute the response of a linear or linearized model subjected to harmonic excitation for one or several frequencies.

For example, in solid mechanics, it is used to compute the frequency response of a mechanical structure with respect to particular load distributions and frequencies. In acoustics and electromagnetics, it is used to compute the transmission and reflection versus frequency. A Frequency Domain study step accounts for the effects of all eigenmodes that are properly resolved by the mesh and how they couple with the applied loads or excitations. The output of a Frequency Domain study step is typically displayed as a transfer function, for example, magnitude or phase of deformation, sound pressure, impedance, or scattering parameters versus frequency.

The zero level on the dB scale varies with the type of fluid. That value is a reference pressure that corresponds to 0 dB. This variable occurs in calculations of the sound pressure level L_p based on the root mean square (rms) pressure p_{rms} , such that

$$p = 20 \log \left(\frac{p_{rms}}{p_{ref}} \right) \text{ with } p_{rms} = \sqrt{\frac{1}{2}} p p, \quad (1)$$

where p_{ref} is the reference pressure and the star represents the complex conjugate. This is an expression valid for the case of harmonically time-varying acoustic pressure p .

Select a Reference pressure for the sound pressure level based on the fluid type:

- use reference pressure for air to use a reference pressure of 20 μPa ($20 \cdot 10^{-6}$ Pa).

Impedance

The Impedance node adds an impedance boundary condition, which is a generalization of the sound-hard and sound-soft boundary conditions:

$$-n \cdot \left(-\frac{1}{\rho_c} (\nabla p_t - q_d) \right) = -\frac{i\omega p_t}{Z_i}, \quad (2)$$

q_d q_d – dipole domain source; p_t – total pressure; ρ_c – density (quiescent); ω – cyclic frequency; Z_i – the acoustic input impedance of the external domain and it has the unit of a specific acoustic impedance; n – refractive index. From a physical point of view, the acoustic input impedance is the ratio between the local pressure and local normal particle velocity.

In the Pressure Acoustics, Transient interface using a Time Dependent study, the impedance boundary condition is the following:

$$-n \cdot \left(-\frac{1}{\rho_c} (\nabla p_t - q_d) \right) = \frac{1}{Z_i} \frac{\partial p_t}{\partial t}. \quad (3)$$

Here Z_i is the specific acoustic input impedance of the external domain and it is measured in the SI unit $\text{Pa} \cdot \text{s}/\text{m}$ – pressure divided by velocity. The specific acoustic impedance Z_i is related to the acoustic impedance Z_{ac} (ratio of pressure and flow rate) and the mechanical impedance Z_{mech} (ratio of force and velocity) via the area A of the boundary, according to

$$Z_{mech} = A^2 Z_{ac}. \quad (4)$$

The Impedance boundary condition is a good approximation of a locally reacting surface, a surface for which the normal velocity at any point depends only on the pressure at that exact point.

Most impedance models only exist in the frequency domain. The only exception is the user defined impedance which can be applied also in the time domain.

The sound pressure level

The sound pressure level $L_{p,i}$ in the i th element is

$$L_{p,i} = 10 \log \left(\frac{\rho c I_{w,i}}{p_{ref,SPL}} \right), \quad (5)$$

where ρ is the density of the fluid, c is the speed of sound, and $p_{ref,SPL}$ is the reference pressure corresponding to 0 dB. Note that the base-10 logarithm is used. One can create own geometry or use geometry from literature sources.

Results

The sound pressure level (SPL) calculated at 100 Hz is shown in Figure 2.

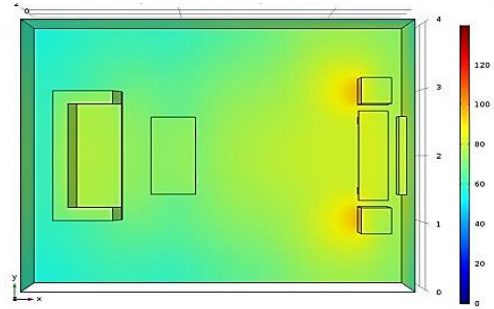


Fig. 2. Room with sound propagation at 100 Hz

At a frequency of 100 Hz, the sound level is between 45 and 85 dB. In most of the room, the sound level is 65 dB. At a distance of 2 meters from the source, the sound decreased by 5 dB.

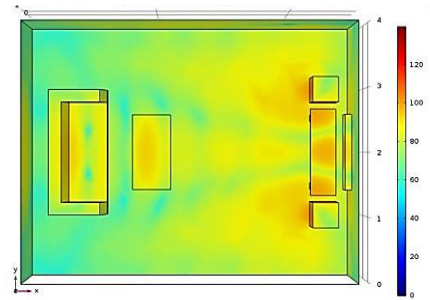


Fig. 3. Room with sound propagation at 300 Hz

As can be seen in Figure 3, at a frequency of 300 Hz the sound pressure level is between 60 and 100 dB. Near the loudspeaker and the listener, the noise spreads best. Most of the room is 80 dB.

Figure 4 shows that at a frequency of 500 Hz, the noise level is 60 to 100dB. In the greater area of the room, sound varies from 65 dB to 90 dB.

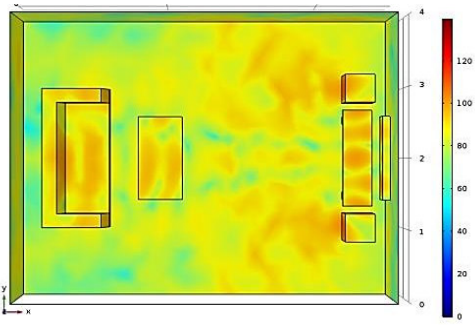


Fig. 4. Room with sound propagation at 500 Hz

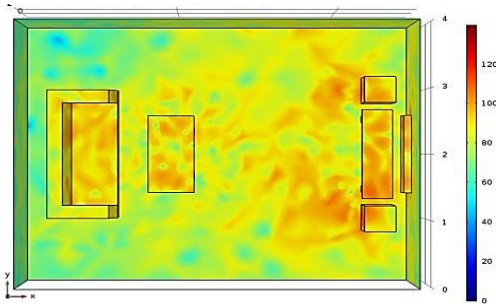


Fig. 5. Room with sound propagation at 1000 Hz

Figure 5 shows the effect of sound at 1000 Hz. In the greater area of the room the sound varies from 80 to 95 dB.

Figure 6 shows a room with the frequency of sound at 1000 Hz. Most rooms correspond to the spectrum of blue color, the sound level of which is from 0 to 20 dB, the maximum sound level is 100 dB. The attenuation occurs 2 m from the noise source.

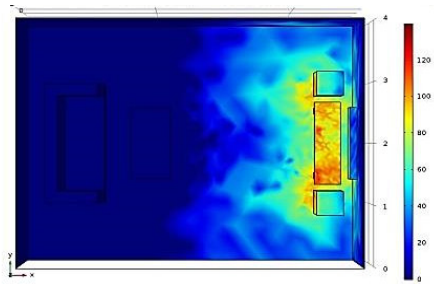


Fig. 6. Room with sound propagation at 5000 Hz

The results of this research show that up to a certain frequency the sound increases to 1000 Hz, and then it begins to decay.

The Eigenfrequency study and study step are used to compute eigenmodes and eigenfrequencies of a linear – or linearized – model.

In acoustics, the eigenfrequencies correspond to the resonant frequencies and the eigenmodes correspond to the normalized acoustic field at the eigenfrequencies. The relevant quantity when it comes to placing the loudspeakers is the amplitude of the standing pressure wave. A sound source excites an eigenmode the most if it is placed in one

of the pressure antinodes for the mode. Conversely, with the source in a pressure node, the eigenmode remains silent.

All modes have local maxima in the corners of an empty room so speakers in the corners excite all eigenfrequencies. This simulation predicts eigenmodes that strongly resemble those of the corresponding empty room.

Figure 7 shows that near the sofa eigenfrequency increases; the acoustic pressure is 2 Pa and also increases in the corner of the room (about 2.5 Pa). In the center of the room eigenfrequency is 1.6 Pa. In these places of the room there is an effect of increasing the pressure several times.

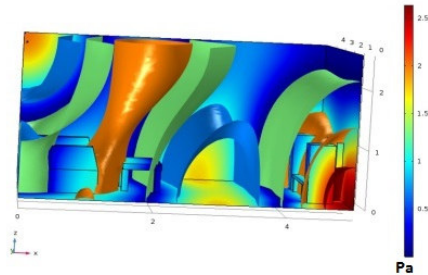


Fig. 7. The sound pressure distribution for an eigenfrequency of 99.5 Hz

Oliva *et al.* (2011) suggest that the highest SPLs (spatial variation difference between maximum and minimum sound pressure level at resonance frequency) were usually found in the corners, but the SPL measured in a corner was not necessarily a maximum. Indeed, SPL differences between corners were at some times between 10 and 20 dB. The spatial variation of SPL diminished exponentially with the frequency. The maximum SPL variation was typically found in the first room mode, at the lowest resonance frequency. The absorption and fittings affected the sound field. The incident path of the noise became more important and the maximum SPLs are observed in its vicinity when the amount of absorption in the room increased (Oliva *et al.* 2011). The current study also shows the difference in the corners and the source of noise lie between 10 and 20 dB.

Conclusions

Comsol features a great deal of flexibility when dealing with any physical problem. Comsol program requires deep knowledge of physics, allowing to solve problems at the fundamental level. ANSYS is an industry oriented product providing rapid solutions to acoustic problems. The Comsol Multiphysics program could be used to analyze the propagation of sound. The acoustic module in the Comsol Multiphysics program allows simulation of the

conditions of the surrounding scene with a noise source, as well as solves problems with the measurement of an acoustic wave. The Roomsim program is a free, open-source educational tool for educators and students in audio signal processing, music technology, auditory perception, psychoacoustics, room acoustics, and digital signal processing.

Odeon can be used to create models of sound on a large scale which is suitable for modeling concert halls, theatres, churches and mosques.

In the current research, a room with different sound frequencies from 100 to 5000 Hz was simulated. The results of the research showed that the sound pressure level increased from low to medium frequency (between 45 and 85 dB at a frequency of 100 Hz) in most of the room; at a frequency of 500 Hz sound varied from 90 dB to 65 dB. Thereafter the sound pressure level decreased together with frequency drifts. At a frequency of 5000 Hz from 0 to 20 dB, the maximum sound level is 100 dB, minimum sound pressure is observed, which is associated with a decrease in the wavelength co-occurring with a decrease in frequency.

Analysis of eigenfrequencies shows that near the sofa the natural frequency increases, the acoustic pressure is 2 Pa and it also increases in the corners of the room. High-frequency eigenmodes are located in the corners of the room and in the center of the room, near the couch.

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AKUSTINIŲ RODIKLIŲ PATALPOSE MODELIAVIMAS NAUDOJANT COMSOL MULTIPHYSICS

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Santrauka

Modeliavimo programos suteikia daugybę galimybių imituoti akustines sistemas. Šiame straipsnyje buvo apžvelgtos programos, naudojamos įvairiems akustinių parametrų modeliavimo tikslams pasiekti. Aprašytos tokios programos, kaip *Sound PLAN*, *AFMG Sound Flow WinFLAG*, *Comsol multiphysics*, *ANSYS*, *Roomsim*. Nagrinėjamas pavyzdys rodo akustinių rodiklių patalpoje modeliavimą. Buvo atsižvelgta į patalpos parametrus, garso lygį, garso sklaidos greitį ir kt. Pateiktos galimybės naudotis programa *Comsol Multiphysics*. Tyrimų rezultatai parodė, kad aukščiausias dažnis būdavo nustatomas kambario kampuose ir centre. Nustatytas garso slėgio lygio padidėjimas esant žemo ir vidutinio dažnio diapazonui. Esant 5000 Hz dažniui, užfiksuotas mažiausias garso slėgis, kuris susijęs su bangos ilgiu.

Reikšminiai žodžiai: garso slėgio lygis, impedansas, programa *Comsol Multiphysics*, patalpų akustika.