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Modelling of sound propagation of technical systems for real-time VR-applications

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1. Introduction

Acoustical product properties get more and more into the focus of product development. In many cases the sound level in front of a machine has to be reduced. The sound radiated on the outside of the machine is, of course, generated inside by functional or technological processes.

Engineers can affect the acoustical behaviour along the sound propagation chain (Fig. 1). The manipulations of the sound generation by changing the process or geometrical parameters as well as the sound transmission through the structure are primary arrangements, because these arrangements usually have the major influence. However, often it is not possible to manipulate these parameters, and then only secondary measures, i.e. after sound generation and radiation are possible. Examples are establishing additional isolation walls or housings. The main acoustical effects by use of these arrangements are transmission loss and diffraction [1].

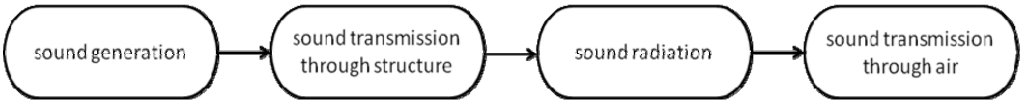

Fig. 1 Sound propagation chain

To get a first impression of the effect of such secondary arrangements, a simulation of the acoustical behaviour and an auralisation of expected results help. A good impression of the acoustics can be produced by the use of extended Virtual Reality (VR). Therefore real-time simulation of the behaviour is necessary. At Ilmenau University of Technology a novel audio-visual VR-System was built which can auralise a known acoustical behaviour together with the geometry by the use of wave-field synthesis [2, 3].

In this work two methods for the simulation of isolation walls are discussed. The first is a real-time simulation based on a simplified analytical model. For the second model the numerical Finite Element Method (FEM) is used. In this paper the simulation is limited to a 2D-simulation and point sources. In the simulation, all influences of the environment were ignored, so only free-field conditions are considered.

The simulation models under VR conditions have to fulfil the following requirements:

- the simulation or the results have to be applicable in real-time;
- the simulation models have to be parametrisable by geometrical and acoustical relevant characteristics (e.g. bending stiffness);
- the necessary accuracy is given by the psycho-acoustical perception.

The simulation models are discussed for a simple sound source and the isolation wall (Fig. 2). In this example the focus is on diffraction effects, because – due to the thickness of the isolation wall – transmission effects are very small.

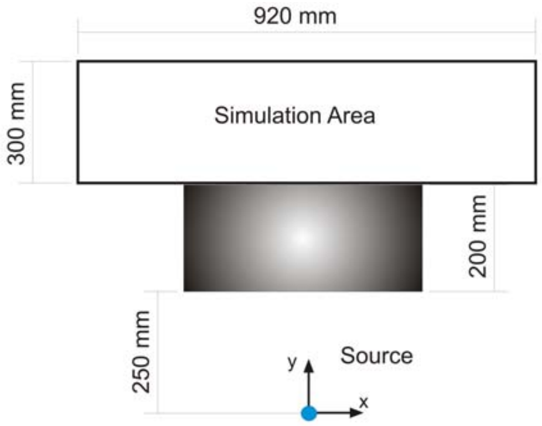

Fig. 2 Geometrical representation of the simulation set-up

2. Analytical model

The analytical model is based on a separation of the calculation of diffraction and transmission loss. The results of both simulations are superposed.

The basic approach for the diffraction model is the diffraction at a semi-infinite wall (Fig. 3). The problem is treated as a two-dimensional problem, i.e. the sound-field in the z-axis is assumed constant $\frac{\partial p}{\partial z} = 0$. By using these assumptions the wave equation can be transformed to cylindrical coordinates as [4, 5]

$$r^2\frac{\partial^2 p}{\partial r^2}+r\frac{\partial p}{\partial r}+\frac{\partial^2 p}{\partial \phi^2}+k^2r^2p=0 \tag{1}$$

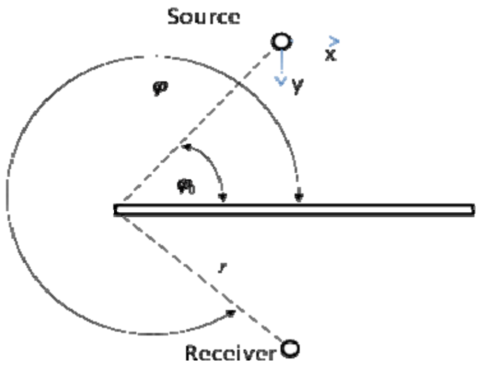

Fig. 3 Scheme of diffraction at a semiinfinite wall

This equation can be solved using the Bessel function [6]:

$$p\left(r,\varphi\right)=p_Q\left(0\right)\sum_{n=0}^{\infty}\frac{2e^{in\frac{\pi}{4}}}{\varepsilon_n}J_{\frac{n}{2}}\left(kr\right)cos\left(n\frac{\varphi}{2}\right)cos\left(n\frac{\varphi_0}{2}\right) \tag{2}$$

with $\varepsilon=\begin{cases}2\,\text{for}\ n=0\\1\,\text{for}\ n>0\end{cases}$, k is wave number, J the Bessel function, angles see Fig. 3.

For higher orders of n, the Bessel function is close to zero for small radii. Therefore, the sum can be truncated for high numbers of n.

This approach can be extended for more complex geometries having further edges and considering the restrictions of the simplification. In this case, in the simulation all paths between the source and the receiver as well as the angles at the edges have to be detected and superimposed.

For the calculation of the transmission loss elementary geometries of walls or housings with a homogeneous material distribution are assumed. Then the transmission loss only depends on the thickness of the wall and the incidence angle (Fig. 4) as well as the acoustic parameters of the obstacle. Based on these parameters the linear loss-factor t can be calculated [4]

$$p_2=p_1t \tag{3}$$

$$t=\frac{\dfrac{2i\rho c}{m''\omega}}{\left(\dfrac{k^4}{k_B^4}sin^4\varphi_0-1\right)cos\,\varphi_0+\dfrac{2i\rho c}{m''\omega}} \tag{4}$$

with $k_B=\frac{m''}{B'}\omega^2$, $m''=\rho h$, $B'=\frac{E}{1-\mu^2}\frac{h^3}{12}$

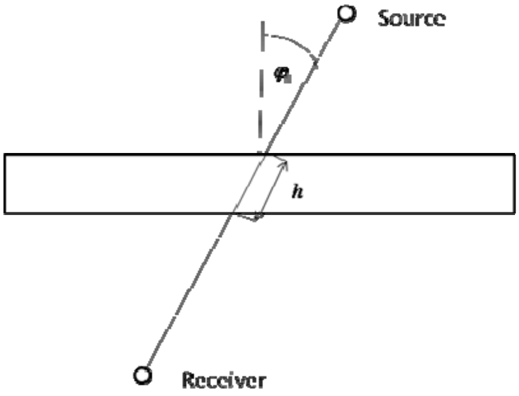

Fig. 4 Scheme of transmission losses

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For the simulation, besides the detection of the entrance and outlet point as well as the angle φ_0, the evaluation of the material parameters (ρ, E, μ) is necessary. These parameters can be stored with the geometrical representation.

3. FEM model

The interaction of structure (obstacle) and acoustic media in the formula of Finite Elements is described as follows [1]

$$\begin{bmatrix}[M_e] & [0]\\ \rho_0[R_e]^T & [M_e^P]\end{bmatrix}\begin{Bmatrix}\{\ddot{u}_e\}\\ \{\ddot{P}_e\}\end{Bmatrix}+\begin{bmatrix}[C_e] & [0]\\ [0] & [C_e^P]\end{bmatrix}\begin{Bmatrix}\{\dot{u}_e\}\\ \{\dot{P}_e\}\end{Bmatrix}+\begin{bmatrix}[K_e] & -[R_e]\\ [0] & [K_e^P]\end{bmatrix}\begin{Bmatrix}\{u_e\}\\ \{P_e\}\end{Bmatrix}=\begin{Bmatrix}\{F_e\}\\ \{0\}\end{Bmatrix} \tag{5}$$

where $\left[M_e^P\right]$, $\left[M_e\right]$ are matrices of the mass of the acoustic medium and structure respectively; $\left[C_e^P\right]$, $\left[C_e\right]$ are damping matrices of the acoustic medium and structure; $\left[K_e^P\right]$, $\left[K_e\right]$ are stiffness matrices of the acoustic medium and structure; $\rho_0\left[R_e\right]^T$ is relation matrix of the acoustic medium and the structure; $\left\{P_e\right\}$ is vector of pressure in the nodes and its derivatives $\left\{\dot{P}_e\right\}$, $\left\{\ddot{P}_e\right\}$ with regard to time; $\left\{u_e\right\}$ is vector of nodal displacement and its derivatives $\left\{\dot{u}_e\right\}$, $\left\{\ddot{u}_e\right\}$ with regard to time; $\left\{F_e\right\}$ is the load vector; ρ_0 is density of air medium. After the theoretical model was established, the FEM software ANSYS 10 was used to perform the numerical simulation. The analysed two-dimensional model consists of acoustic and structural media (Fig. 5). In order to model these, the elements FLUID29, FLUID129 and PLANE42 are used.

As the acoustic package FEM of the ANSYS 10 software does not take into account the loss of sound energy when the sound is transmitted through the obstacle, the methodology used for this model is specified in [7, 8]. According to this methodology, when pressure of the incident sound wave is known, the loss of sound pressure is calculated when the wave passes from one medium to another, and the value of sound pressure is determined on the boundary of mediums. According to the scheme of the process shown in the Fig. 6, which would be the sound

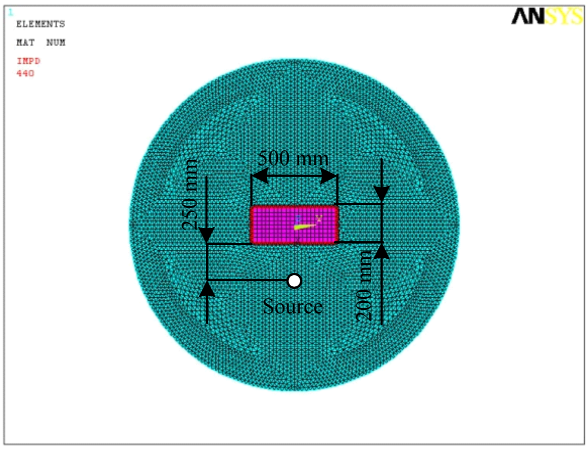


Fig. 5 FE-model of acoustic and structural media

pressure on the junction of the second and third medium. In such a way, firstly the system is excited by the sound source of certain size and frequency, and the field of sound pressure is determined in the closed space, as well as on the boundary between the incident wave and structural medium (boundary between the first and the second medium in the Fig. 6).

According to the presented data, when the aforementioned methodology is used, the loss of sound pressure is calculated when the sound wave passes through the structure, as well as the values of sound pressure on the boundary of the second and third mediums (Fig. 6).

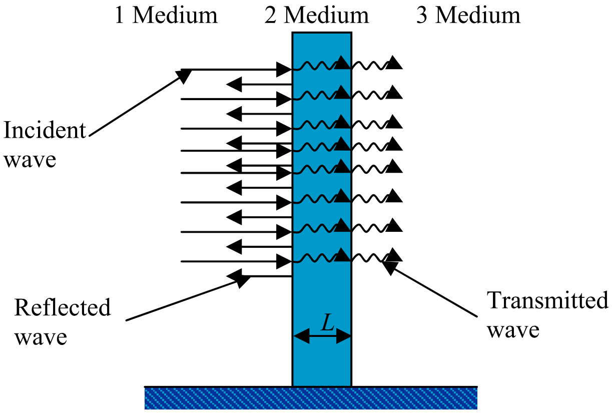


Fig. 6 Scheme of sound transmission from the first medium to the third through the second medium

The sound transmission loss expresses the power transmission coefficient of the sound in decibel units [7]

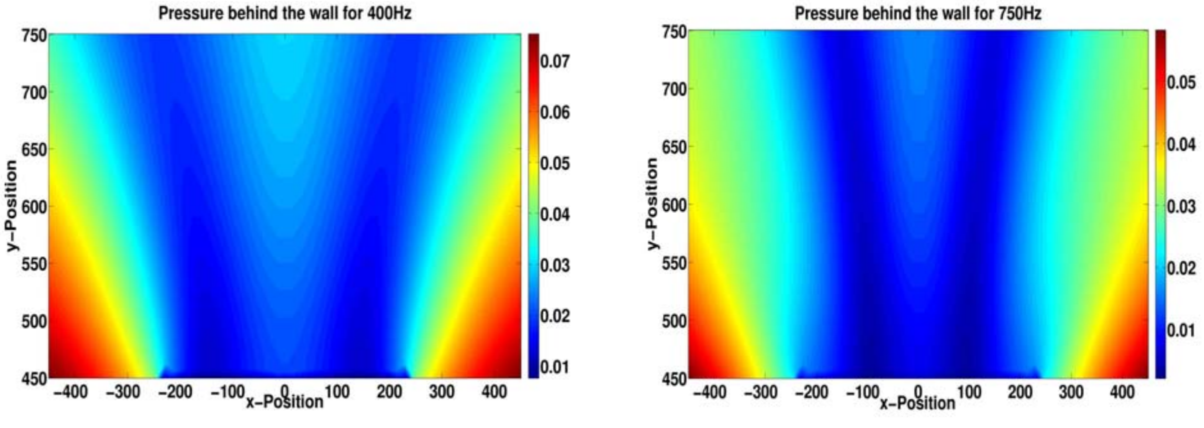
$$TL = 10\,log_{10}\,(1/a_t) = 10\,log_{10}\left(\frac{\left(1+\frac{Z_1}{Z_2}\right)cos^2\,(k_2 L) + \left(\frac{Z_1}{Z_2}+\frac{Z_2}{Z_3}\right)^2 sin^2\,(k_2 L)}{4(Z_1/Z_3)} \right) \tag{6}$$

where k is the wave number in the medium, L is the thickness of the obstacle, Z_1, Z_2, Z_3 are characteristic impedances of the 1st, 2nd and 3rd media, respectively.

Secondly these values of sound pressure on the boundary of the second and third mediums are used to excite and calculate sound pressure in the acoustic medium once more. Eventually, the values of sound pressure calculated in the first and second stages are summarised using the principle of superposition, and the complete acoustic field in the closed space containing the obstacle is calculated taking into account the loss of sound energy when the sound wave passes through the obstacle. In order to automate the calculations using the methodology [9], the ANSYS macro file was created. This allowed making the calculations much faster.

4. Comparison of the models

Both simulation results look qualitatively similar (Figs. 7 and 8). The positions of the maximum and minimum sound pressure are nearly the same. Differences can be found in the progression of the sound pressure and the absolute pressure level. Deviations can also be found in the analytical model at the crossover of one diffraction to two diffractions. The main reason for this could be that for the diffraction only the edge of the obstacle was considered. For more exact simulation the area around the edge has to be investigated in more detail [10].

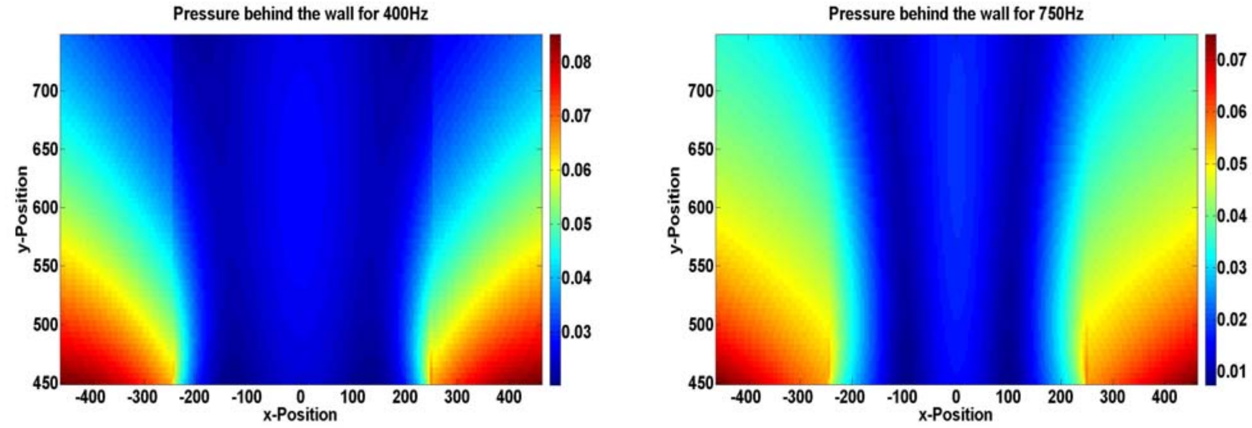


a b

Fig. 7 Sound pressure calculated by the FEM model for a source with white noise ($p(f)$ = 1 Pa) for 400 (a) and 750 Hz (b)

For real-time applications, the calculation time is a crucial parameter. The FEM simulation has to calculate the total area. So the simulation takes about 2 minutes per frequency (5821 nodes).

The analytic model also requires about 2 minutes for the total area with 11100 receiver positions running in Matlab. But for the application in a VR-environment only a few receiver position are necessary and the simulation can be done using C++. So the simulation can be executed in real-time (in the tests 24 ms per receiver position).



a

b

Fig. 8 Sound pressure calculated by the analytical model for a source with white noise for 400 (a) and 750 Hz (b)

5. Use of the models in real-time application

The discussed FEM simulation currently cannot be executed in real-time. So the sound field is pre-simulated for a given source, receiver-field and wall configuration and a white noise characteristic with a gain of 1 Pa. The results are stored in a 3D-matrix with the axis x- and y-position and frequency. During the simulation the current user position can be used to extract only the cells of the matrix which are necessary. Based on the normalisation of the source, the matrix can be used for any source characteristic. Because of the pre-calculation of a scene configuration the source position and the obstacle cannot be modified in real-time: a modification in the set-up requires a new simulation with FEM.

The analytical method can be calculated in real-time. So it is possible to do the simulation directly in the VR-system. During the simulation all edges with geometrical parameters (Fig. 3) between the source and the receiver have to be found. An efficient way to detect the edges is a ray-tracing approach which can be integrated easily into the VR-software. Using the API of the VR-system, the geometrical parameters of the VR-model can be detected and the simulation parameters be calculated.

In the current implementation the tracked user position is used for the receiver. It is also possible to simulate several receiver positions in parallel, but this is not necessary for the given application. The simulation is run in each render frame, but the simulation checks if the parameters of the source, the receiver or the obstacle have been modified before the main simulation is done. This optimisation reduces the render load. The edge detection and calculation of the acoustic parameters is done in a thread. So the simulation has no influence on the rendering performance of the visualisation. This method can even be used for dynamic scenes.

6. Conclusion

In this paper two methods for the simulation of diffraction and transmission losses around and through simple obstacles are discussed. For both methods advantages and weaknesses were presented, as well as the restrictions for their use in real-time applications. Currently real-time VR simulation only can be done with simplified models or pre-calculations. Further research deals with the optimisation of the methods as well as the extension to more complex obstacles.

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S. Husung, R. Mikalauskas, C. Weber, T. Kästner

GARSO SKLIDIMO TECHNINĖSE SISTEMOSE MODELIAVIMAS VR ĮRANGAI PANAUDOTI REALIU LAIKU

Reziumė

Kuriant produktą, vienas iš svarbiausių reikalavimų yra ore sklindančio techninių sistemų generuojamo triukšmo mažinimas. Tam tikslui yra naudojamos užtvaros ir garsą sugeriančios pertvaros. Projektuojant labai naudinga, jei šių priemonių įtaką būtų galima nagrinėti ir įvertinti naudojant virtualų prototipą (vietoj fizikinio prototipo). Šiame darbe lyginami du metodai (analitinis ir skaitmeninis), taikomi triukšmo mažinimui modeliuoti realiu laiku virtualios realybės sistemoje. Be to, aptariami būtini modeliavimo aspektai ir idėjos realizavimo apribojimai.

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MODELLING OF SOUND PROPAGATION OF TECHNICAL SYSTEMS FOR REAL-TIME VR-APPLICATIONS

Summary

An important challenge during product development is the reduction of air-borne noise generated by technical systems. This could be done by enclosures or sound isolation walls. The design process would benefit a lot if the effects of these arrangements could be studied and evaluated by methods of virtual prototyping (instead of physical prototypes). This paper compares two methods (one analytical and one numerical) to simulate the noise reduction for real-time investigations in an enhanced Virtual-Reality-System. Furthermore, the necessary steps for the simulation and also limitations of the concepts are discussed.

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МОДЕЛИРОВАНИЕ РАСПРОСТРАНЕНИЯ ЗВУКА В ТЕХНИЧЕСКИХ СИСТЕМАХ ДЛЯ ИСПОЛЬЗОВАНИЯ ВР ОБОРУДОВАНИЯ В РЕАЛЬНОМ ВРЕМЕНИ

Резюме

В процессе проектирования изделия одним из важнейших требований является уменьшение шума, генерируемого технической системой и распространяющегося в воздухе. Для этой цели используются заграждения и звукопоглощающие барьеры. В процессе проектирования очень полезно, если есть возможность анализировать и оценить влияние этих элементов с помощью виртуального прототипа (вместо физического). В работе сравниваются два метода (аналитический и численный), используемые для моделирования уменьшения звука в реальном времени в системе виртуальной реальности. Также обсуждаются необходимые аспекты моделирования и ограничения реализации идеи.

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