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SIMULATION OF ACOUSTICAL PRODUCT PROPERTIES FOR TECHNICAL SYSTEMS IN VIRTUAL ENVIRONMENTS

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ABSTRACT

Virtual Prototyping is an important tool to verify and optimize product properties in the early design phases. By using digital product models many simulations of the system behavior can be carried out (instead of physical testing) and therefore development cost and time can be reduced. For the development of innovative complex technical systems the applied models should comprehend the most important product properties. Today there are still deficits in modeling and evaluating the acoustical behavior of technical products which is particular important for consumer goods and automobile industries.

A flexible audio-visual projection system was configured which combines stereoscopic visualization in a CAVE with a new spatial acoustic reproduction method: wave-field-synthesis (WFS). This technology enables a realistic sound impression which is independent of the position of the listener. For this, a scene representation is needed that provides the sound reproduction synchronously with the visualization of machinery, cars and other technical systems.

This paper describes the goals of the new audio-visual Virtual Reality (VR)-system and its use as an innovative tool for a realistic representation and presentation of audio-visual product properties, even in early design phases. The paper is mainly focused on methods to describe acoustical product properties of technical systems for an interactive presentation in real-time Virtual Reality during design process.

Keywords: Virtual Reality, Virtual Prototyping, Acoustics, Model representation, Design optimization

1 INTRODUCTION

Today, product development is dominated by reducing time and cost, which could be contradictory to the required high standards of solution quality. The use of computer-based tools enables the simulation of product properties and their optimization before first physical prototypes are built. Representing simulation results by the use of (extended) Virtual Reality (VR) technologies have advantages – especially if both the simulation tools and the VR representation are multimodal (e.g. in our case: visualization plus acoustics) – so that an enhanced immersion in the virtual scene becomes possible. Furthermore, this enables an easy comprehension and understanding of complex contexts and relations, which otherwise might be only clear for experts. Using intuitive interaction tools, the user can navigate in the VR scene, manipulate and investigate the scene content.

Present VR-systems are often limited by only using stereoscopic projection as visual interface of information. Even if a large amount of visual perception is covered very well, only information about geometry and geometry-related behavior (e.g. motion = geometry changes in time) can be transferred. The spectrum of the perception should be extended, because nowadays more realistic immersion and presence are expected in VR environments. Therefore, in research some efforts are made to add haptic and acoustic perceptions to VR-systems.

In very many cases, product development has to take the acoustic behavior of technical systems into account. Very often the allowed noise level of a machine is already limited by law and/or ergonomic considerations. Besides the noise level as such, an efficient analysis of the frequency response must be considered for acoustic product evaluation. In other cases, a "nice sound" is desired and has to be "sound-designed" into the product (e.g. motor cars, bikes, household machinery, …).

All this is, at present, mostly done by experience. So dependable statements are only possible after the manufacturing of first prototypes. Therefore, the goal is to include acoustic analysis and synthesis in the early phases of engineering design by means of virtual prototyping.

For audiovisual investigations in VR are needed:

- models which include the acoustical behavior for steady as well as non-steady states of the product,
- a system for the spatial audio-visual presentation.

In the following section a system is described which supports this type of investigations. Furthermore, some new methods are presented which were developed to simulate sound transmission as well as sound radiation effects considering the directional characteristics of the original object.
The overall goal is to analyze and optimize the acoustic product properties together with the geometry and the functional properties in relation to external conditions. The engineer wants to optimize the properties by manipulating the design parameters of the product. So the VR system and the representation have to update the product properties and present them to the engineer interactively immediately after the parameter modification.

2 AUDIOVISUAL VR SYSTEM FOR VIRTUAL PROTOTYPING

In 2006 a novel VR system was erected at the Competence Centre Virtual Reality of Ilmenau University of Technology (figure 1). This is a flexible 3-screen stereoscopic projection system for visualization in combination with spatial sound presentation based on the wave-field-synthesis (WFS) principle [3, 4, 5].

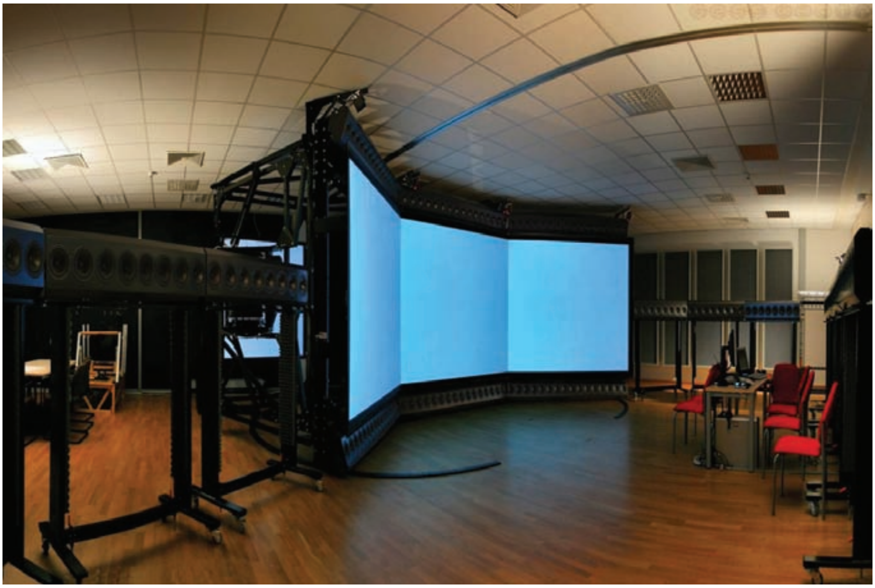


Figure 1. Audio-visual VR-system at the Competence Centre Virtual Reality of Ilmenau University of Technology

To reproduce sound events spatially, different principles are possible. The most common method generates the sound via a few loudspeakers. Different loudspeaker setups are possible, the most established are the 2/0 stereophony as well as the 3/2 stereophony. All these setups have restrictions:

- Sound events in the space between listener and loudspeakers are almost not reproducible.
- Furthermore, the strongly restricted hearing zone limits the application because only few people (those within the so-called sweet spot) get a spatially correct sound impression.

Another concept is the binaural acoustic. This principle provides a realistic hearing impression for mostly one user by calculation of the HTRF (Head-Related Transfer Function) [19] from the tracking data. The HTRF takes into consideration the head and outer ear form, from this generating sound pressure and time differences of the sound individually for each ear. For this technology often headphones are used which limit the movement area and which hinder communication between actors in the VR environment.

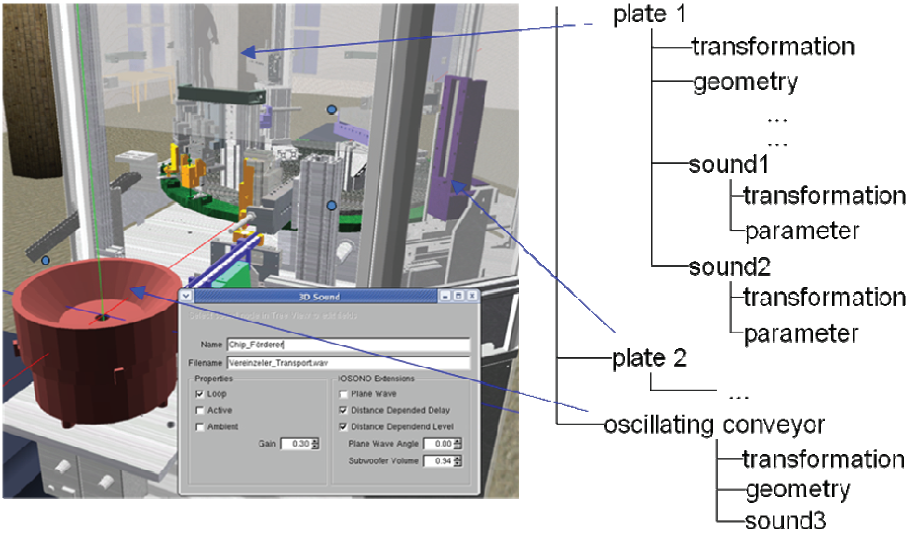
The wave-field-synthesis principle overcomes these limits by generating the complete surrounding sound field. Wave-field-synthesis is an acoustic reproduction concept for realistic sound fields in any virtual environment based on Huygens' Principle of wave-theory [3]: A (real) primary sound source can be represented by overlaying an infinite number of secondary sound sources. In reality, these sources are replaced by a limited number of loudspeakers. The condition for the reproduction of the sound field is a closed arrangement of a high number of loudspeakers around the listener area. The system in Ilmenau comprises of up to 208 loudspeakers. Based on the Kirchhoff-Helmholtz integral of wave theory the sound field can be calculated [4, 5].

This new technology enables a realistic sound impression independent of the listeners' position. This controllable and spatial playback of sound sources (gears, engines, bearings, etc.) is a capable tool for machine acoustics analysis and sound design. The user can manipulate the VR-scene interactively because the wave-field-synthesis algorithm performs "acoustic rendering" in real-time.

An important research issue at the Competence Center Virtual Reality of Ilmenau University of Technology is to investigate and develop the application of wave-field-synthesis for machine acoustics simulation and sound design. For this task special models have to be developed.

3 INITIAL WORK

For the audio-visual VR installation presented in section 2, enhanced product models have to be developed, almost nothing (beyond visualization) is off-the-shelf. This has been going on stepwise since 2006/2007. The first virtual product models including acoustics were established on the basis of existing machine tools and utility vehicles produced by cooperating companies. 3D-CAD models are the basis for generating the geometrical VR representations and the functional modeling of the respective systems. In order too represent acoustical information in the virtual product model the available scene graph was enhanced [11]: The acoustical information was accommodated in the form of special VRML-nodes, the scene graph now is also containing acoustic parameters like volume and spatial position. For WFS several other parameters like distance-dependent loudness or sound emission angle for plane waves are necessary (see figure 2) [8].



Name: Chip_Förderer
Filename: Vereinzeler_Transport.wav
☑ Loop
☐ Active
☐ Ambient
Gain 0.30
☐ Plane Wave
☑ Distance Depended Delay
☑ Distance Dependend Level
Plane Wave Angle 0.00
Subwoofer Volume 0.34

Figure 2. Audio-visual model of a revolving automatic assembly machine

The description of the acoustic scene by means of single sound sources enables the interactive manipulation of parameters, which leads on a real-time basis for the adaptation of the sound field. Audio nodes are placed spatially along with the geometry of the corresponding machine components or in the connection points between two components as well as on the surface of complicated devices and machines. In the scene graph the audio nodes are related to the geometry nodes or common assembly nodes, so that these will be moved according to the movement of the geometry in the scene [8].

Real components have a sound radiation which is more complicated than simple (punctiform) audio nodes. Hence, in the first approach to include directional characteristics of the sound radiation the VR scene was divided into several areas; in each of them the sound field is assumed nearly constant. These areas are called “portals”. Figure 3 shows the main portals of a revolving automatic assembly machine. The main user of the audio-visual VR installation is head-tracked; if he/she enters a portal, the VR software selects the corresponding sound sources, so that the sound field is adapted to the relative position of the listener and the machine [11].

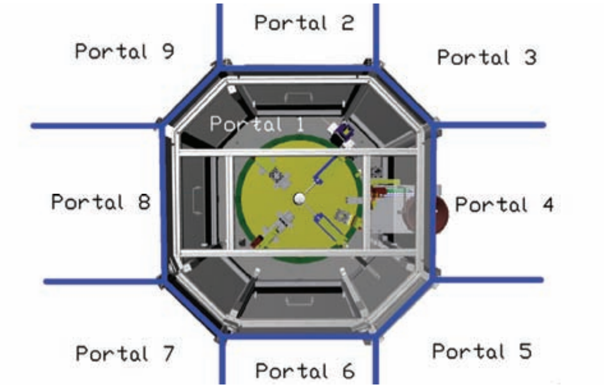


Figure 3. Portals in the model of a revolving automatic assembly machine

The first models briefly described in this section were entirely based on empirical, i.e. measured data of existing components. Distinctions between structure-borne and air-borne sound, between different sound sources inside one component or even pre-calculations of sound generation and transmission could not be considered. But these models are an important base for further research. First results will be presented in the next sections.

There exist several investigations, also at other research units, in modeling parts of the sound propagation. But currently there is no final set of modeling methods and tools for the sufficiently realistic calculation of acoustic product properties from the sources to the auralisation in VR. Still many steps are necessary to reach this goal.

4 AUDIOVISUAL PRODUCT MODELS

Hearable sound is a mechanical vibration in the frequency range of 20 … 20,000 Hz. Depending on the medium, sound is differentiated in structure-borne sound, fluid-borne sound and air-borne sound. The sound which is directly hearable always is air-borne noise. This sound can either be radiated directly from a sound source (so-called direct radiation) or the sound stems from a remote sound source inside the technical system and is transmitted to the surface via structure-borne or fluid-borne sound. At the surface the sound is then transformed to air-borne sound. This type of sound transfer is called indirect sound radiation. Indirect sound radiation is the main focus in the area of machine acoustics. For the understanding of the process it is good to build a model of the sound propagation chain (figure 4). The main focus on modeling the sound propagation in this paper is the sound generation, transmission through the structure and the radiation on the surface.

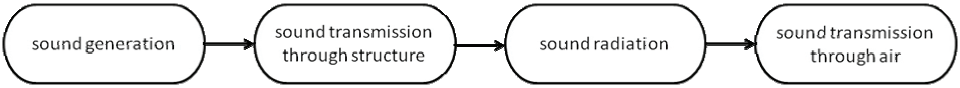


Figure 4. General sound propagation chain

In technical systems the sound generation normally is produced by shocks, friction, mass-forces (e.g. unbalances), roll-contacts, self-excitation or combinations of them. Depending on perceptional limits and possible update rates of the model, these types of sound generation have to be modeled as short-time or harmonic signals.

For the modeling of the sound propagation for each component the sound generation sources have to be detected. A component in our case can be a motor, a gearbox, etc. The sound source can be the result of a working process inside the considered component which in this case is an acoustically active component. For each component also structural vibrations can be induced at the interfaces from the neighboring components. This structural vibration also is radiated partly over the surface of the component. The other part is dissipated or emitted over other interfaces. So for the radiation the sound from the inner sound source as well as the structural vibration from other components have to be overlayed (figure 5).

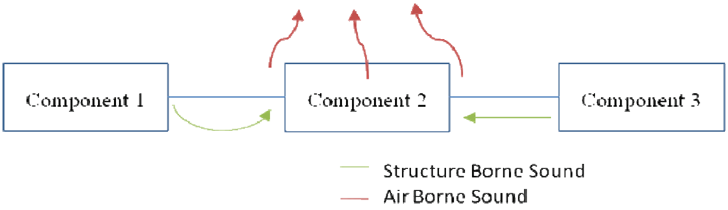


Figure 5. Overlaying different sound events (here: for component 2)

For the consideration of all structure-borne sounds, models are needed which describe the sound transfer inside the component as well as sound induced via the interfaces of the component. These models have to interact with each other.

The sound generation and the sound transmission always depend on the current state of the component. This state is defined by functional input and output parameters like rotational speed and external loads, by (quasi-) static characteristics like geometry and material as well as by environmental conditions like temperature, humidity, etc. So for describing the state of the component a further model is necessary. This must at least contain an elementary (dynamic) functional model in connection with some geometry parameters.

The overall model for each component is visualized in figure 6.

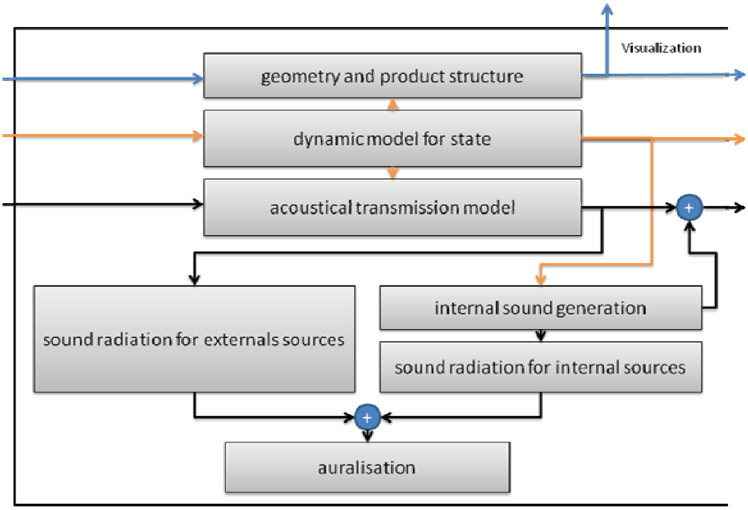


Figure 6. Model for representation and simulation of audiovisual product properties

For the sum of all models mentioned the following requirements have to be fulfilled:

- Calculation in real-time
- Description from an engineering point of view
- Modular and general description of the behavior for the use in a wide range of technical systems
- Interactive manipulation of parameters

In the following section two small parts of the model will be explained a bit more in detail. The first is the acoustic transmission model for describing structure-borne sound through the components. The second deals with the sound radiation considering directional characteristic.

5 ACOUSTIC TRANSMISSION MODEL

The basic equation to calculate structure-borne sound transmission through a component is:

$$v(f) = H(f) * F(f) \tag{1}$$

where v is the oscillation velocity – mostly normal to the surface –, H the transfer function and F the excitation force

The transfer function H is, in principle, highly non-linear. However, evaluating H with methods that can consider non-linear behavior (e.g. FEM) is currently not possible in real-time. Therefore, a necessary, in our problem area usually well fitted assumption for the calculation of structure-borne sound in real-time is that all components behave Linear-Time-Invariant (LTI) [17]. Only then it is possible to work with linear transfer functions as well as handle each frequency or frequency range separately.

An alternative would be to pre-calculate the structure-borne sound transfer using non-linear methods and deduce linear transfer functions which are then used for real-time evaluation ("homogenization" of the problem).

Many approaches in literature work with unidirectional transfer functions to calculate structure-borne sound transfer (see equation 1). It is a very time-efficient way, but it is not possible to handle feedback effects from the load on the source and the component itself [16].

In the area of electrical networks another method was found: Each component is described as a two-port or four-pole [18]. A two-port has two ports or "power interfaces" to neighboring components. Each port transports one effort and one flow variable (therefore "four-pole"). The product of the effort and the flow variable at the same port is the power transmitted at that port. In general, between the two pairs of poles of a two-port or four-pole, there is a black box describing the transfer function inside the component. In the following section the term four-pole is used.

The four-pole approach can be used as a means to establish multi-domain (e.g. mechatronic) behavior models of systems [20, 21]. The same approach can also be used in the area of acoustics in order to describe the structure-borne sound behavior. A general four-pole for an acoustic system is shown in figure 7.

Figure 7. Simple four pole with a source and a load impedance

Inside the four-pole, usually a linear transfer behavior is assumed. In this case the behavior can be calculated with:

$$\begin{pmatrix} F_2 \\ v_1 \end{pmatrix} = \begin{pmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{pmatrix} \begin{pmatrix} F_1 \\ v_2 \end{pmatrix} \qquad (2)$$

In equation (2), F_i are the forces at the four-pole interfaces and v_i the related velocities. G_{ij} are the four-pole coefficients.

For simple abstract systems like an elementary linear spring the coefficients G_{ij} can be calculated analytically. This is nearly not possible for real systems. Therefore, the coefficients G_{ij} are interpreted as linear complex-valued transfer function components and impedances. Each coefficient is a vector. These vectors contain the linear functions of the considered frequencies. The multiplication with the force and velocity is done element-wise.

For the calculation of the transfer function for several components the four-poles have to be coupled (figure 8).

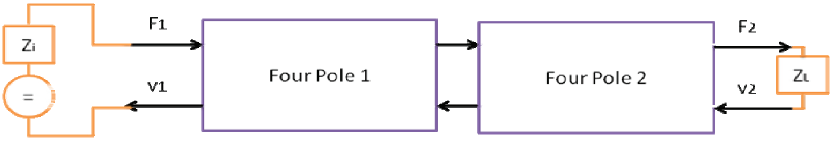


Figure 8. Coupling of two four-poles

In general, a body has six degrees of freedom. So twelve input and output variables are necessary to describe the behavior exactly. Then the four-pole becomes a twelve-port (or 24-pole) with a matrix of 144 elements. In many cases the number of considered degrees of freedom can be reduced. So often the four-pole representation is sufficient.

For the integration of this method into the audio-visual model the simulation tool Matlab/Simulink can be used. Each four-pole is a subsystem with specific input/output parameters. In the higher levels of the Simulink model, the individual four-poles can be connected to a network. Figure 9 shows the realization of one four-pole in Matlab/Simulink. For the flexible manipulation of its coefficients they are provided by a self-defined function, considering parameters from the dynamic model (see figure 6). The various four-pole parameters are stored in a database.

In the overall model the results of the structure-borne sound calculation can be used to calculate the sound radiation.

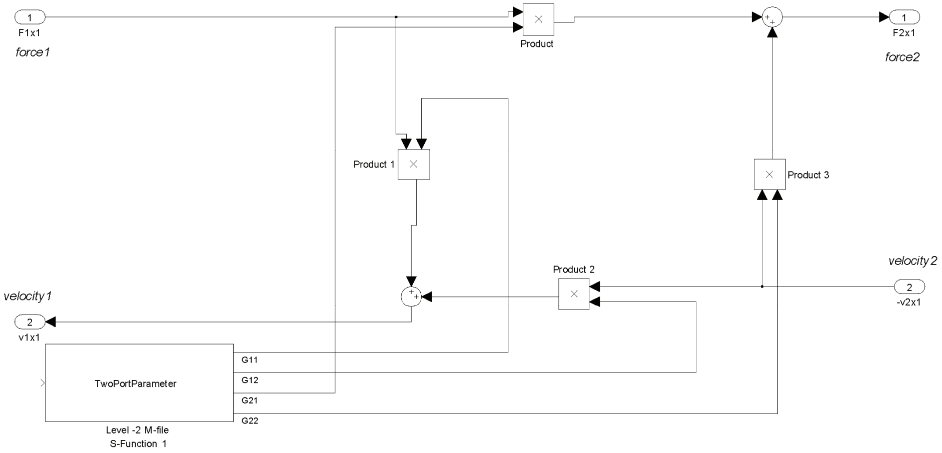


Figure 9. Realization of the four-pole using Matlab/Simulink with flexible parameters via external calculation

As a first example the four-pole network for connecting a motor to a gearbox with load was developed. The required parameters were acquired by measurements, in this case via a special measuring setup using laser vibrometer, impact hammer, accelerometer and microphone at a 3D-handling system. Data Acquisition was realized by a mobile system offering four fast scanning channels (sample rates up to 51,2 kHz) in combination with a self-developed software tool called "noiseDAQ" (Matlab based). Using this equipment it was possible to acquire time signals and evaluate frequency response behavior [2]. For the simulation only the vibration in vertical direction (radial to the shaft) was considered (see figure 10).

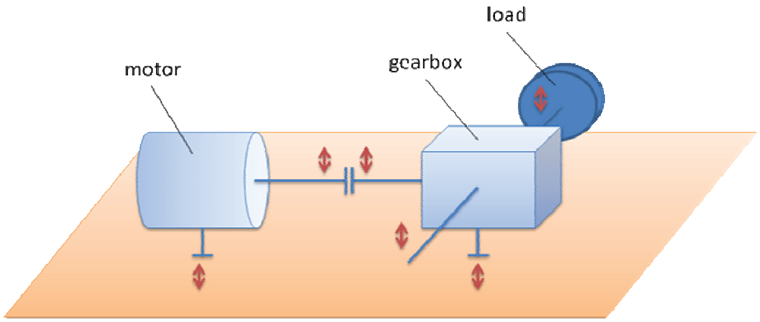


Figure 10. Principle of the measuring setup

A big advantage of the four-pole representation is the relative small load on the calculation performance of the computer. Consequently, it is possible to simulate the complete system in real-time. Another advantage is that the mechanical engineer is quite familiar with the modeling style of the system. The coefficients of the four-pole (G_{ij}) represent the behavior of the component, the engineer can manipulate them in order to change and optimize the behavior.

Further investigations were done to optimize the parameter determination and to handle components with a bigger number of interfaces and with larger dimensions.

6 SOUND RADIATION AND AURALISATION

Another important part of the model of audio-visual product properties is modeling the sound radiation: How do vibrations of the component surface induce vibrations of the surrounding air? Because of the object geometry and the position of the several sound sources the radiated sound field usually has a marked directional characteristic.

For the calculation of the emitted sound based on the pressure and velocity on the surface several methods were developed by other researchers. These are for example:

- Elementary radiator based on Helmholtz integral or Rayleigh principle [14]
- Acoustic finite-element method (AFEM)
- Statistical energy analysis (SEA) [12]
- Boundary-element method (BEM) and
- DFEM [9] using the Rayleigh principle.

These principles offer a very good calculation of the sound field around a technical product based on the known velocity distribution on the surface. But most of the methods have the problem that the calculation is much too time-consuming to be implemented in real-time environments.

For calculating sound radiation by approximation, but in real-time, it is also possible to use the linear transfer function approach. Transfer functions can be measured or calculated in pre-processes using the methods like listed above. For our investigations the transfer functions depend on the dynamic state of the systems, calculated in the dynamic model, and the structure-borne sound conditions at the interfaces of the components. The output of the radiation calculation is the sound pressure in the air, which can be auralised in the VR-system using the wave-field-synthesis algorithm.

For a realistic presentation of the acoustic product behavior also the directional characteristic should be considered. There exist two main concepts using wave-field synthesis:

- Adaption of the wave-field-synthesis algorithms [1, 13]
- Representation with a model based on monopole sources describing the directional characteristic via superposition of several elementary (punctiform) sound sources

The first concept enables a good reproduction of the directional radiation characteristic. Considering the tracking data it enables also a good reproduction above the aliasing frequency of the acoustic VR installation [13]. But for this method the known characteristic in the VR-model has to be transferred to the wave-field-synthesis renderer with special algorithms synchronized with the position of the virtual model and the acoustic data.

The second concept has the advantage to represent the behavior using a small number of simple (punctiform) sound sources placed directly in the VR scene-graph in combination with the geometry of the component. With a special version of this concept, the so-called monopole synthesis [6], it is also possible to use the standard wave-field-synthesis algorithm for the reproduction. The disadvantage of this method is, however, the lower accuracy of reproduction, because it is not possible to represent a complex radiation exactly if only based on a small number monopoles.

For the investigations described below the second method was used.

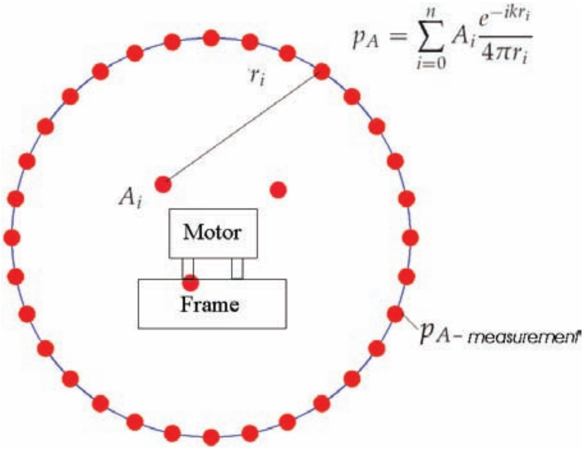
The idea of the monopole synthesis is to calculate positions and complex amplitudes of a small number of monopoles based on the known directional characteristic of an object [6] (see figure 11). The approach based on the superposition of monopole sources (point sources) is:

$$p_A = \sum_{j=0}^{n} A_j \frac{e^{-ikr_j}}{4\pi r_j} \tag{3}$$

with A_j being the complex amplitude and r_j the distance between the monopole and the reproduction point.

Figure 11 shows the superposition of three monopoles in the inner of a sphere. Each pressure p_A on the sphere is the sum of the three monopoles multiplied by the Green's function depending on the distance between the two points and the frequency. The raw data for the calculation is gained via simulation or measurements.

Figure 11. Principle of monopole-synthesis, shown for the example of a motor



For the detection of the complex amplitudes several methods can be used, like pseudo-inverse or minimum error between original and reproduced sound field. According to our experiences the method of the minimum error offers the best results for the accuracy.

$$J(A) = \sum_{m=1}^{M} \left(p_{A-reprod}(r_m) - p_{A\_vorh}(r_m) \right)^2 \tag{4}$$

First investigations have been done with a two-way loudspeaker (figure 12). Using a one-microphone sphere array [15] it was possible to measure the characteristic of the loudspeaker with a white-noise stimulus.

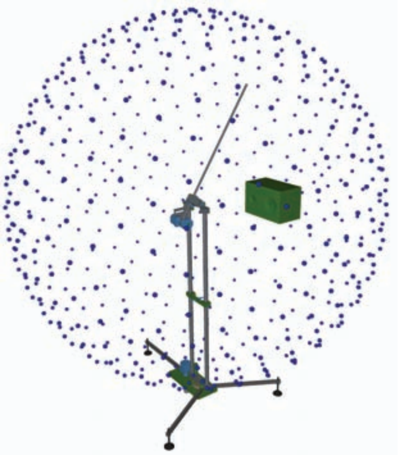


Figure 12. Measurement setup

The calculation was done in Matlab based on algorithms of Giron [6] and Schlesinger et al. [15] and for the real-time coding in native C++. Here for each relevant frequency a matrix is calculated which represents the transformation of the sound field on the sphere surface to the monopole sources.
Figure 13 shows the comparison of the original (left) and the reproduced (right) data for the sound field at 960Hz [8] plotted against the azimuth and elevation angle for 16 monopoles.

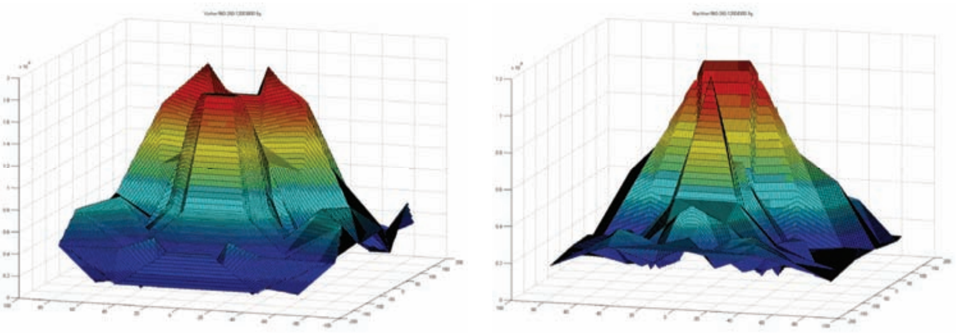


Figure 13. Measured (left) and reproduced (right) characteristic of the two-way loudspeaker

Further investigations were done together with the University of Applied Sciences in Ulm for the auralisation of a gearbox, simulated with boundary-element method in pre process [7].

7 CONCLUSIONS

Virtual Prototyping connected with the use of extended Virtual Reality opens new doors for the evaluation of technical systems in the product development. Stereoscopic projection and real-time interaction with the virtual scene complemented with acoustic reproduction are powerful tools in the early phases of engineering design.
Following features and new possibilities are available using the FASP system:

- Real-time interaction and visualization of scenes including sound reproduction
- Design reviews with efficient recognition of geometrical and acoustical product properties and failures
- Efficient interdisciplinary work by easy understanding of complicated contexts
- Efficient education and training using realistic virtual prototype

In this paper some important steps for the realization of an audio-visual product model for interactive investigation in VR were presented. With this model the engineers were supported doing investigation in sound design and optimization of machine acoustic based on virtual prototypes.
There are still deficits in modeling the product behavior especially for larger components with several interfaces as well as the ascertainment of the necessary parameters. The necessary investigations are one focus of the ongoing research.

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