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AURALISATION OF ACOUSTICAL PRODUCT PROPERTIES FOR TECHNICAL SYSTEMS IN VIRTUAL ENVIRONMENTS

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ABSTRACT

Today product development is dominated by reducing time and costs, which can be contradictory to the required high quality standards of products. The advantages of using computer-based tools enable the simulation of product properties and their optimisation before first physical prototypes are built. The presentation of those simulation results using (extended) Virtual Reality (VR) technologies is very helpful - especially if both the simulation tools and the VR representation are multimodal (e.g. visualisation extended by 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.

Current VR-systems are often limited by only providing visual information. Even if a large amount of visual information is covered very well, only geometry and geometry-related behaviour (e.g. motion = geometry changes in time) or abstract information can be transferred. However, in many cases product development has to consider the acoustical behaviour of technical systems. Applications of this can be found in the noise engineering (noise control or noise limitation of products) as well as in the sound design engineering of products (so called "brand sound").

Due to the increasing importance of acoustics and the expectation of a more realistic immersion and presence in VR environments the sense of perception should be extended. For this a research group was built in Ilmenau consisting of mechanical engineers as well as acoustical engineers at Ilmenau University of Technology in the engineering design group as well at the Fraunhofer Institute for Digital Media Technology (IDMT).

The goal of the research work is to add acoustical representations to VR-systems for technical applications, integrating the acoustical analysis and synthesis in the early phases of engineering design process by means of virtual prototyping. For the audio-visual representations in VR environments there are two important fields being investigated by the research group:

- Research and development of product models including acoustical behaviour for steady and non-steady states of the product,
- Research and development of methods and models for the adaptation of the acoustical behaviour of products in a spatial, immersive and interactive audio reproduction system for VR environments.

This contribution discusses the use of a particular VR-system using the Wave Field Synthesis (WFS) technology for the sound reproduction. Besides this, necessary simulation methods as well as models of sound generation and transmission through the structure will be discussed. Those simulation models and methods are used for the representation of acoustical product properties for real-time auralisation via WFS. This provides means for the optimisation and modification of system parameters.

A pick-and-place unit (see figure 1) was taken as an example of an ongoing product development process, findings using this example are in the focus of this paper.

Index Terms— Virtual Reality, Machine Acoustic, Auralisation, Simulation in Design

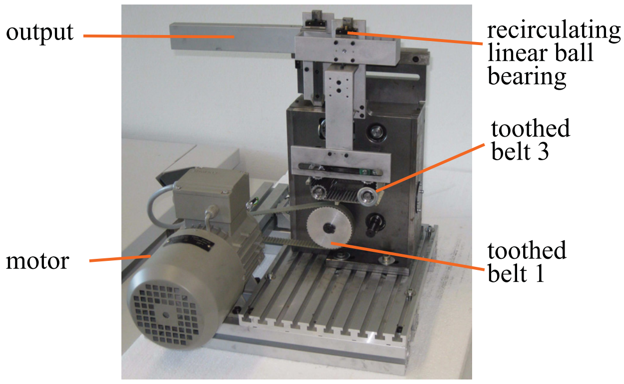


Fig. 1. Pick-and-place unit as application example

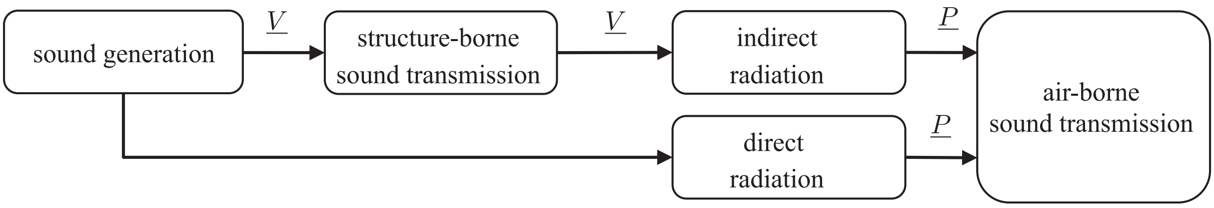


Fig. 2. General sound propagation chain with V the oscillation velocity and P the pressure

1. INTRODUCTION AND GOALS

One goal in product development is to get statements about the product behaviour in early phases of the design process. Therefore the challenge is to provide suitable simulation models and methods, here focusing on the representation of acoustical behaviour of products. The model representing the acoustical properties of the product must be rendered in real-time in order to enable interaction and modification of relevant design and acoustical parameters (geometry, material, sound directivity, etc.).

There exist several investigations in the field of modelling sound propagation [1, 2, 3], but currently there is no final set of methods and tools for a sufficiently realistic pre-calculation of acoustical product properties of technical systems from the sources to their (especially multi-user) auralisation in VR.

This paper discusses the main steps of modelling the sound propagation chain (see figure 2) in VR for the example of a pick-and-place unit which mainly consists of typical machine elements (bearings, gear drives, toothed belts, linear guides, ...) and which consist mostly of metal.

2. SOUND REPRODUCTION USING WAVE FIELD SYNTHESIS

Wave Field Synthesis is a spatial sound reproduction technique that uses a large number of loudspeakers, called secondary sources, to (re)create wave fronts of virtual sound sources (also called primary sources) [4]. All loudspeakers surrounding the listening area are driven by an individual signal. The superposition of the loudspeaker signals creates the wave front of the virtual source in the listening area. In contrast to existing sound reproduction technologies like stereo and 5.1 surround sound, the listener can move around freely and will always perceive a correct spatial image of the virtual acoustic scene [5, 6, 7].

Common practical WFS systems allow simultaneously rendering of many virtual sources. However, the synthesis is still restricted to basic primary source types like monopoles and plane waves. Real-world sound sources radiate sound to certain directions with different intensities. This frequency dependent behaviour is called directivity and has an strong influence on the perception of sound sources. Therefore, if you think about an immersive, acoustical VR-system, the reproduction of directional sound sources is significant. In the following a two-dimensional approach for Wave Field Synthesis of directional sound sources is given.

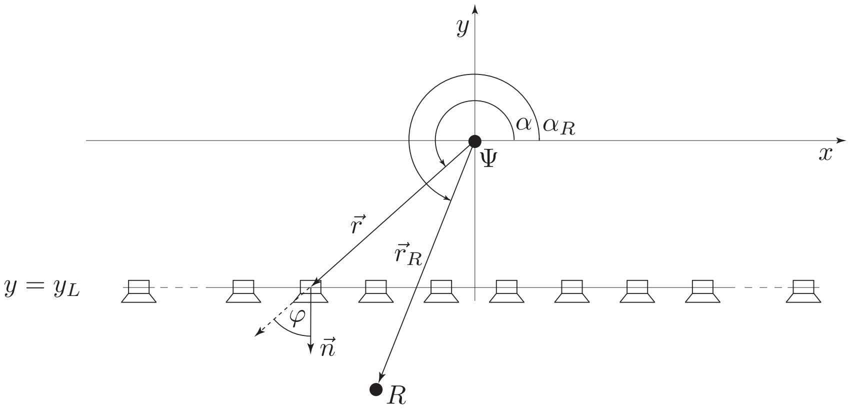


Fig. 3. Geometry for the derivation of Wave Field Synthesis driving functions. The sound field of the primary source Ψ will be synthesised in the xy-plane at position R using a linear array of loudspeakers having normal vector $\vec{n}$.

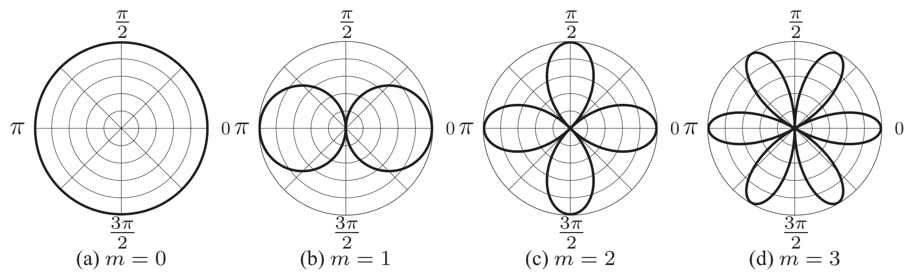


Fig. 4. Illustration of the first four circular harmonic angular basis functions. The plots show $|\Re(e^{jm\alpha})|$ on the unit circle for the orders $m = \{0; \ldots; 3\}$.

2.1. Synthesis of virtual sound sources with arbitrary directivities

Each wave field radiated by a sound source, that only has a 2D dependence, can be described by a circular harmonics expansion [8]. For the description of the primary source sound field only an outgoing wave field will be present. Assuming the geometry shown in figure 3 and the primary source to be in the origin of the coordinate system the following equation holds:

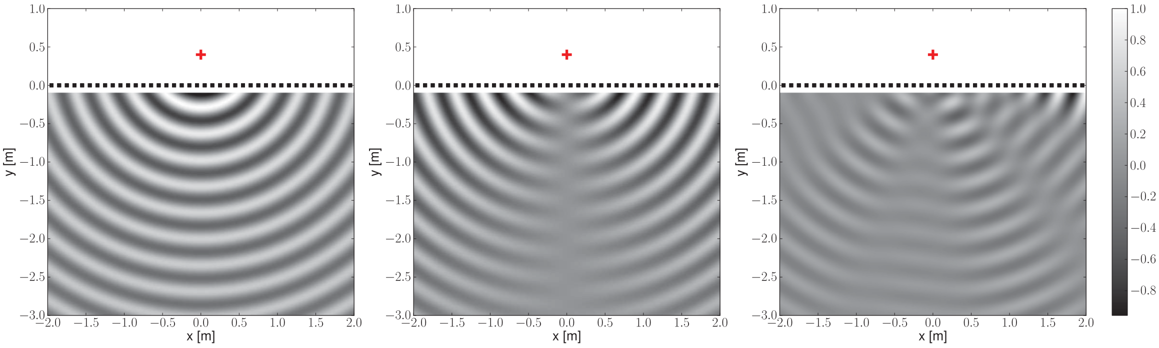
$$\underline{P}_{\Psi}(\vec{r}_R, \omega) = \underline{S}(\omega) \sum_{m=-\infty}^{\infty} \underline{\breve{C}}_m^{(2)}(\omega) \underline{H}_m^{(2)}(k|\vec{r}_R|) e^{jm\alpha_R}. \tag{1}$$

In here $\underline{S}(\omega)$ is the output signal of the primary source in the frequency domain, $\underline{H}_m^{(2)}(k|\vec{r}_R|)$ is the mth order Hankel of second kind describing the radiation, $k = \omega/c = 2\pi f/c$ the wave number with the speed of sound c. The last term is the angular basis function that is depicted in figure 4 for different integer orders of m. In equation (1) $\underline{\breve{C}}_m^{(2)}(\omega)$ are called the circular harmonics expansion coefficients, which are complex weighting factors for the creation of complex directivity patterns using a superposition of basis functions. The superscript (2) denotes an outgoing wavefield.

The basic synthesis equation is given by the Rayleigh I integral. Assuming an infinite line of secondary monopole line sources and the geometry depicted in figure 3 it can be written:

$$\underline{P}_R(\vec{r}_R, \omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \underbrace{j\omega\rho \underline{V}_{\vec{n}}(\vec{r}, \omega)}_{\text{primary source}} \underbrace{\left(-j\pi \underline{H}_0^{(2)}(k|\vec{r}_R - \vec{r}|)\right)}_{\text{secondary source}} dx. \tag{2}$$

It states, that a secondary source distribution of monopole line sources can synthesise the wave field of a primary source if the velocity $\underline{V}_{\vec{n}}(\vec{r}, \omega)$ at the secondary source positions, according to the normal $\vec{n}$, and the density of the propagation medium ρ are known. The relation between the velocity and the pressure of a sound source is given



(a) Monopole
$\underline{\breve{C}}_0^{(2)} = 1; \underline{\breve{C}}_{m\neq 0}^{(2)} = 0$

(b) Dipole
$\underline{\breve{C}}_{\{-1;1\}}^{(2)} = 1; \underline{\breve{C}}_{m\neq\{-1;1\}}^{(2)} = 0$

(c) Multipole
$\underline{\breve{C}}_{\{-5;\ldots;5\}}^{(2)} = 1; \underline{\breve{C}}_{m\neq\{-5;\ldots;5\}}^{(2)} = 0$

Fig. 5. Simulation of synthesised sound fields radiated by a primary source (red cross) using a line array of secondary sources (black squares). The simulation shows three different directivity patterns of the primary source for a frequency of 1.000 Hz. (a) monopole, (b) dipole, (c) complex multipole.

by the equation of motion:

$$j\omega\rho\underline{V}_{\vec{n}} = -\frac{\partial \underline{P}_\Psi(\vec{r}_R,\omega)}{\partial|\vec{n}|} \equiv \underline{Q}(\ldots). \tag{3}$$

The secondary source driving function $\underline{Q}(\ldots)$ (also called WFS operator) will therefore be defined as the gradient of the circular harmonics expansion in direction of the secondary source normals $\vec{n}$. This results in an operator that uses linear monopole line sources to synthesise the sound field of a line source with an arbitrarily directivity pattern [9]. In real-world applications loudspeakers are used as secondary sources. These behave more like point sources, if the emitted wave length is large compared to the dimensions of the speakers [10]. In our context also the primary sources that will be auralised, namely the pick-and-place unit, is assumed to behave more like a point source due to their small size. Using the large argument approximation of the Hankel function in the description of the primary and secondary source, these line sources can be exchanged by point sources if a spectral correction, and a listener dependent gain correction is applied [11]. This approximation is only valid for $kr \gg m$ [12]. Using this approach and the geometry depicted in figure 3 the secondary source driving function in the frequency domain yields [13]:

$$\underline{Q}(\vec{r},\vec{r}_R,\alpha,\omega) = j\frac{\sqrt{|\vec{r}_R-\vec{r}|}}{\pi}\cos\varphi\frac{e^{-jk|\vec{r}|}}{\sqrt{|\vec{r}|}}\underline{S}(\omega)\underbrace{\sum_{m=-\infty}^{\infty}\underline{\breve{C}}_m^{(2)}(\omega)j^m e^{jm\alpha}}_{\underline{G}(\alpha,\omega)} \tag{4}$$

with the synthesis integral using secondary point sources:

$$\underline{P}_R(\vec{r}_R,\omega) = \int_{-\infty}^{\infty}\underline{Q}(\vec{r},\omega,\alpha)\frac{e^{-jk|\vec{r}_R-\vec{r}|}}{|\vec{r}_R-\vec{r}|}dx. \tag{5}$$

In equation (4) $\underline{G}(\alpha,\omega)$ is the directivity term. The radiation of the primary source is described by $e^{-jk|\vec{r}|}/\sqrt{|\vec{r}|}$ weighted by an angular dependent cosine term. As a result of the large argument approximation $\sqrt{|\vec{r}_R-\vec{r}|}$ defines a gain correction factor according to a listener position R. The synthesis equation states, that the sound field of the primary source Ψ can be synthesized correctly in terms of phase in the region $y < y_L$, if Ψ, the secondary sources and the listener R are all in the xy-plane. The pressure of the primary source can only be synthesised correctly for position R. Figure 5 shows a numerical simulation of three different directivity patterns for a single frequency of 1.000 Hz.

2.2. Circular Harmonics Decomposition

To determine the circular harmonics expansion coefficients the sound pressure or velocity of the source has to be known on a surrounding circle with radius $|\vec{r}_D|$ [14]. In the following only the decomposition based on pressure values will be regarded. To get rid of the angular dependence of the pressure values $\underline{P}_\Psi(\vec{r}_D,\alpha,\omega)$, a circular

Fourier transformation needs to be applied:

$$\mathring{\underline{P}}_m(\vec{r}_D,\omega) = \frac{1}{2\pi}\int_0^{2\pi} \underline{P}_\Psi(\vec{r}_D,\alpha,\omega)e^{-jm\alpha}d\alpha \tag{6}$$

The decomposition into circular harmonics expansion coefficients describing an outgoing wave field can be performed using:

$$\underline{\breve{C}}_m^{(2)}(\omega) = \frac{\mathring{\underline{P}}_m(\vec{r}_D,\omega)}{\underline{H}_m^{(2)}(k|\vec{r}_D|)}, \tag{7}$$

assuming an incoming wave field that is zero. It can be seen, that the circular harmonics decomposition assumes the radial behaviour of the sound field being decomposed to be that of an ideal line source. As statet above the pick-and-place unit behaves more like a point source. Bringing the large argument approximation of the Hankel function back into mind, it states that the decomposed sound field is a well approximation if it is done in the far-field of the source.

3. MODELS FOR THE SOUND PROPAGATION CHAIN

Audible sound is a vibration in the frequency range of 20 to 20.000 Hz. Depending on the transmitting medium, sound can be differentiated in structure-borne, fluid-borne and air-borne sound. The sound which is directly audible always is air-borne. This sound can either be radiated directly from a sound source (so-called direct radiation) or indirectly. "Indirect sound radiation" means that 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; it is finally transformed into air-borne sound at the surface of a component. Understanding and simulation of indirect sound radiation is important in the area of machine acoustics. For the understanding of the process it is useful to build a model of the sound propagation chain (see figure 2) with the main components sound generation, sound transmission and sound radiation.

3.1. Sound generation

The sound generation can be characterised by the temporal behaviour. It is possible to divide the generation into stochastic, harmonic and transient [15, 16]. In order to be able to manipulate the acoustical behaviour of a technical product or system, the sound generation should be simulated by parametrised models. For the technical system, here the pick-and-place unit as an example, the main sound sources and the stimulation mechanisms have to be detected [17, 18]. In the field of machine acoustics the main stimulation mechanism between components are generated by impact, sequence of impacts, friction and variations of characteristic parameters (like stiffness) and mass-forces.

The simulation of the acoustical product properties is a highly complex procedure, because it is a multi-dimensional problem. The sound generation depends on the temporal progression, the stimulated vibration-force/-velocity as well as the acoustic admittances and the shape of the coupling surface with the structure. In this work the sound sources will be coupled with the structure at one finite point. So the surface is not considered.

In literature several models for the stimulation mechanisms can be found. For the example, the main stimulations of bearings are caused by variations of the radial stiffness during the rotation and deviations of the balls or rings from their ideal geometry [19, 20]. For a gear drive the main mechanism are variations of the teeth stiffness during meshing, meshing impacts, deviations of the tooth forms and surfaces as well as inversion of friction forces [21, 22]. By using the mathematical description of the mechanism, the relevant stimulation frequencies can be calculated using the geometrical parameters and the parameters of the current kinematic state. For the calculation of the amplitudes at the stimulation frequencies, the kinetic state has to be considered. For an overall simulation much more influencing parameters have to be considered, like geometrical tolerances and undulation or 3D load. Currently the models cannot describe all of these parameters and most of the parameters are not fully clear during product development (certainly not in early phases). So the models are restricted to parameters which are known in the relevant development phase and whose effects on the sound generation and propagation are identified.

The investigation shows that some stimulation mechanisms can be simulated using simplified models. However, one main obstacle is the modelling of stochastic or non-steady state effects. In the pick-and-place unit this occurs when modelling the linear guides which are of the recirculating ball type. The main stimulation frequencies of the guides - when driven at a constant linear velocity - are based on rolling natural vibration, yawing, pitching and bouncing [23]. They depend on the geometrical parameters. For many machine-acoustic investigations the

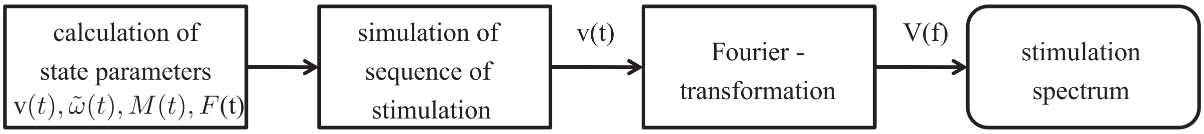


Fig. 6. Simulation of sound generation in time domain and transforming the sequence using the Fourier transformation, with $\mathrm{v}(t)$ - velocity, $\tilde{\omega}(t)$ - angular velocity, $F(t)$ - force, $M(t)$ - moment, $V(f)$ - oscillation velocity

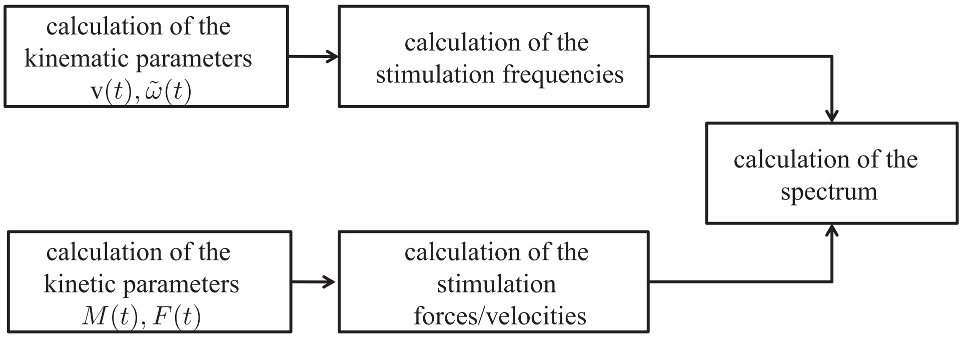


Fig. 7. Simulation of the sound generation by calculation of the spectrum directly in frequency domain, with $\mathrm{v}(t)$ - velocity, $\tilde{\omega}(t)$ - angular velocity, $F(t)$ - force, $M(t)$ - moment

modelling of this stimulation frequencies is enough. However, for acoustic investigations and auralisation of the acoustical behaviour the stimulation frequencies by means of friction and not-steady state processes have to be considered. In many cases it is only possible to use empirical measured data, because the simulation cannot describe the overall generation in a realistic way based on the current state-of-the-art. For measurements, the boundary conditions - like loads and kinematic state - have to be considered and collected.

The sound generation spectrum (stimulation spectrum) can be calculated in two ways. The first way is to simulate the temporal sequence of stimulation and transforming this using the Fourier transformation (see figure 6). The method enables the precise calculation of the frequency spectrum, but it is very time consuming, when the state parameters change very often during the simulation.

A second method deals with the direct simulation of the spectrum for quasi-static states depending on the kinematic [24] and the kinetic state parameters (see figure 7). The method calculates the first stimulation frequency of the spectrum. The spectrum has to be extended by stimulation frequencies with higher order using similarity theorem of the Fourier transformation. This method works very fast, but it is difficult to calculate the forces or velocities of higher order frequencies exactly.

3.2. Sound transmission

The basic equation to calculate structure-borne sound transmission, i.e. propagating sound through a component is:

$$\underline{V}_2(f) = \underline{H}_{12}(f)\underline{F}_1(f) \tag{8}$$

where $\underline{V}_2(f)$ is the oscillation velocity at point 2, $\underline{H}_{12}(f)$ the transfer function between the point 1 and 2 (see figure 8) as well as $\underline{F}_1(f)$ the excitation force at point 1.

The transfer function $\underline{H}$ is, in principle, highly non-linear. However, evaluating H with methods that can consider non-linear behaviour (e.g. FEM [25]) is currently not possible in real-time or could not consider all relevant frequencies (e.g. SEA [26]). 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) [2]. Applying this assumption, 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 then are used for real-time evaluation (”homogenisation” of the problem).

Many approaches in literature work with unidirectional transfer functions to calculate structure-borne sound transfer (see equation (8)). This is a very time-efficient way, but it is not possible to handle feedback effects from

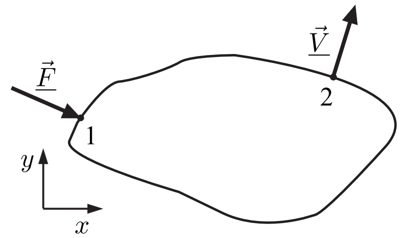


Fig. 8. Sound transmission between two points

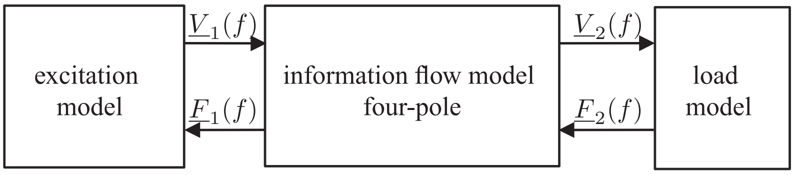


Fig. 9. Simple four-pole with a source and a load which describes the bi-directional sound transmission through the component

the load on the source and the component itself. In the area of electrical and control networks another method was found: Each component is described as a two-port or four-pole [27]. A two-port has two ports or ”power interfaces” to neighbouring 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 (see figure 9).

The four-pole approach can be used to establish multi-domain (e.g. mechatronics) behaviour models of systems [28]. The same approach can also be used in the area of acoustics in order to describe the structure-borne sound behaviour. A general four-pole for an acoustic system is shown in figure 9.

Inside the four-pole, usually linear (or linearised) transfer behaviour is assumed. In this case the behaviour can be calculated with:

$$\begin{pmatrix} \underline{V}_2(f) \\ \underline{F}_1(f) \end{pmatrix} = \begin{pmatrix} \underline{G}_{11}(f) & \underline{G}_{12}(f) \\ \underline{G}_{21}(f) & \underline{G}_{22}(f) \end{pmatrix} \begin{pmatrix} \underline{V}_1(f) \\ \underline{F}_2(f) \end{pmatrix} \tag{9}$$

In equation (9), $F_i(f)$ are the forces at the four-pole interfaces and $V_i(f)$ the related velocities. $\underline{G}_{ij}(f)$ are the four-pole coefficients.

For simple abstract systems like an elementary linear spring, the coefficients $\underline{G}_{ij}$ can be calculated analytically. Often, this is impossible for real systems. Then the coefficients $\underline{G}_{ij}$ are interpreted as linear complex-valued transfer function components and impedances/admittances. 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, several four-poles have to be coupled in a block diagram considering the equilibrium conditions [29]. This is shown in figure 10.

The realisation of the four-pole simulation is done in MATLAB by using standard Simulink toolboxes and user-defined functions for the preparation of the four-pole parameters. Most of the four-pole parameters in the project have been taken from measurements (not simulations) in the first instance. Some four-pole parameters, like those for simple elements (e.g. shafts), are, however, simulated using vibration differential equations. So a direct influence on the mechanical parameters is possible.

The main components of the sound-transmission model for the pick-and-place unit are visualised in figure 11.

3.3. Sound radiation

As described in section 2.2 the sound pressure has to be known on a circle around the virtual object for the extraction of circular harmonics coefficients (see figure 12). The orientation of the circular path will therefore define the plane in which the directivity pattern of the virtual object can be reproduced, using WFS. The sound pressure is a function of the shape and the velocity normal to the surface. Several investigations for such a calculation were published in literature [30, 31].

If the virtual object should be rotated along its elevation angle, the sound pressure has to be determined on a sphere around the virtual object. Figure 13 shows the sound propagation scheme, extended by the auralisation using WFS.

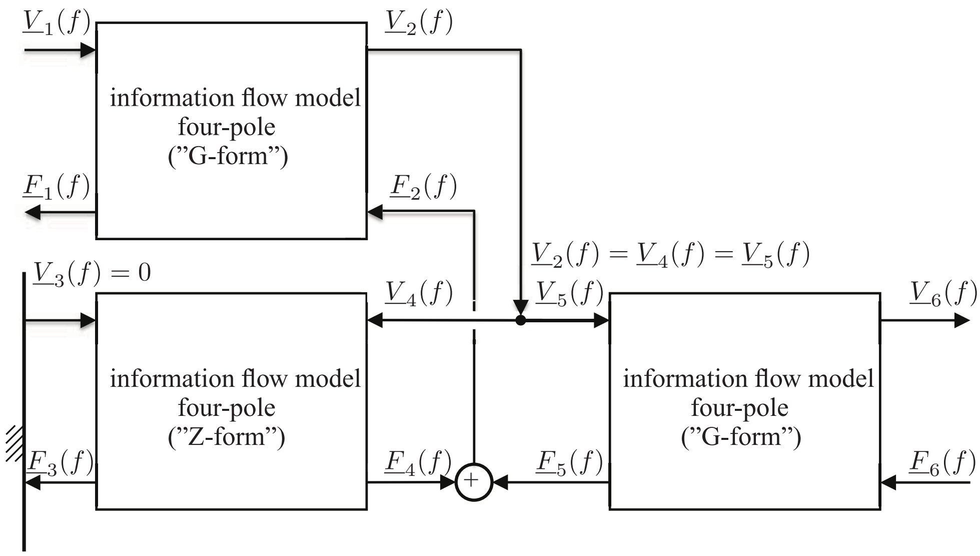


Fig. 10. Coupling of four-poles to build the structure-borne sound network considering the equilibrium conditions

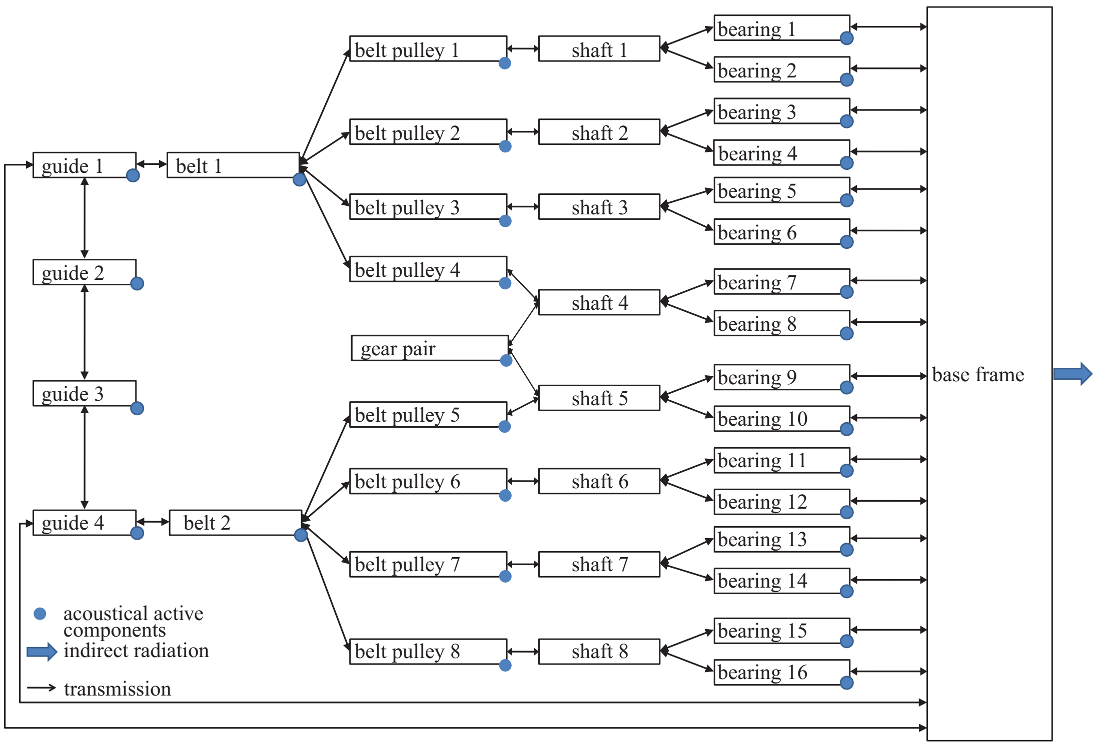


Fig. 11. Sound transmission components of the pick-and-place unit

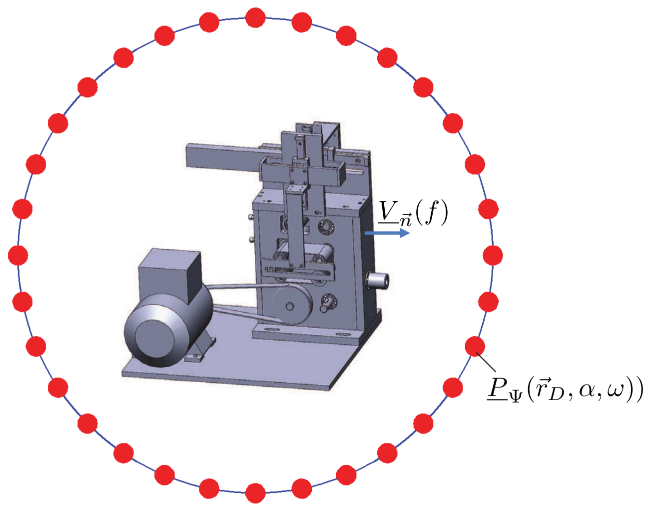


Fig. 12. Simulation of the sound pressure of the pick-and-place unit on a circle around the virtual object. The velocity $\underline{V}_{\vec{n}}$ according to normal $\vec{n}$ leads to the pressure value $\underline{P}_{\Psi}(\vec{r}_R, \omega)$. The orientation of the circular path around the object for which the pressure simulation is conducted defines the plane of reproduction using WFS

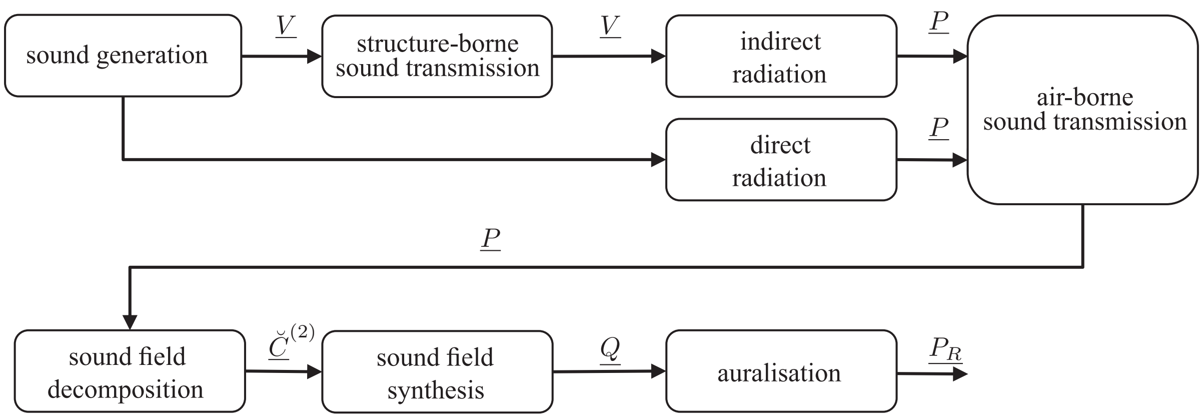


Fig. 13. Sound propagation chain, extended by auralisation process via WFS

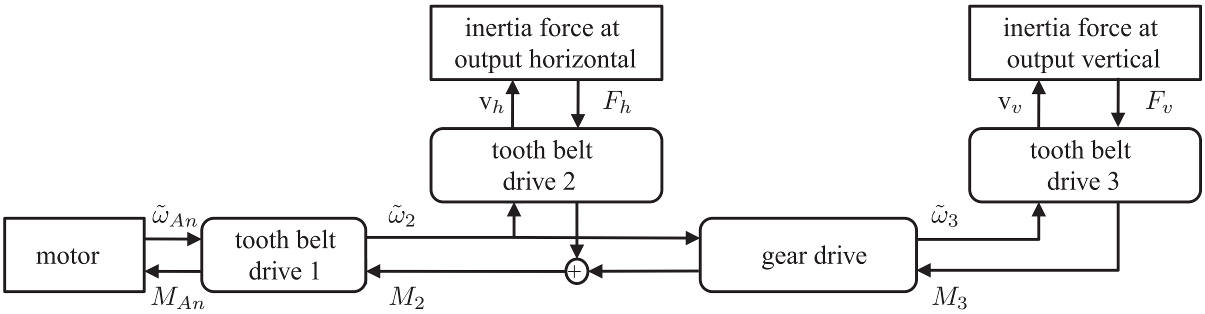


Fig. 14. Schematic of the state model of the pick-and-place unit

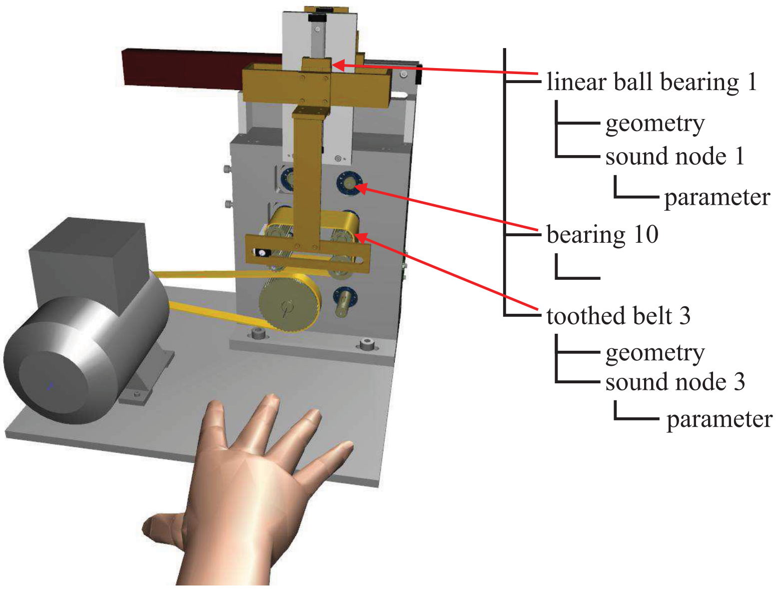


Fig. 15. Extended scene graph of the pick-and-place unit

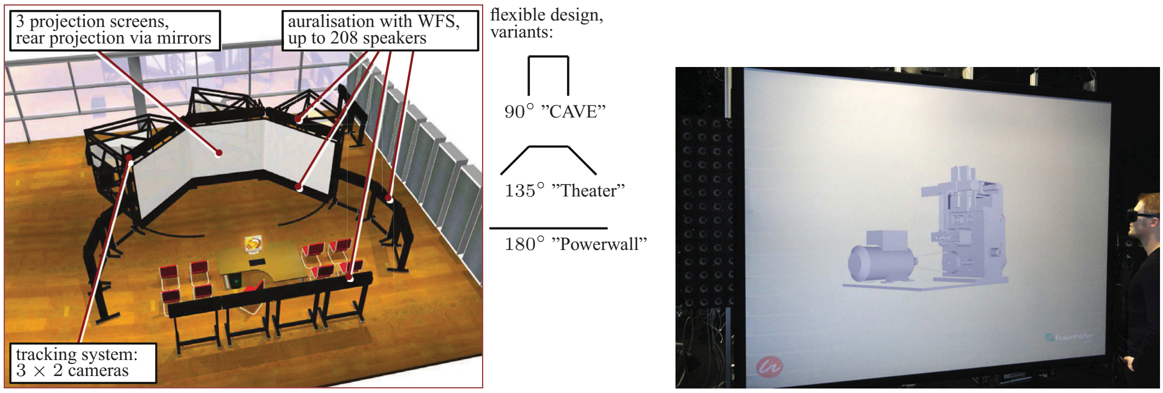
3.4. Model for the state

For the calculation of the sound generation and transmission the current steady and non-steady state of the technical system has to be calculated. So the acoustical model always has to be coupled with a model for the current state (which even has to run before the acoustical properties are assigned). The task of the state-model is to calculate the current kinematic and kinetic parameters and deliver them to the acoustical model [32]. The abstract model for the pick-and-place unit is shown in figure 14. This basically consists of the motor, the gears and the loads.

4. INTEGRATION OF ACOUSTIC INFORMATION IN THE VR-MODEL

3D-CAD models are the basis for generating the geometrical VR-representations and the functional modelling of the respective systems (e.g. the kinematics). In order to represent acoustical information in the virtual product model, the VR scene graph has to be enhanced. Figure 15 shows the extended scene graph of the pick-and-place unit. The acoustical information was accommodated via special VRML (Virtual Reality Modeling Language [33])-nodes. The scene graph now also contains acoustical parameters like the spatial position of sound sources and their (relative) gains. For the WFS representation, several other parameters like distance-dependent sound level modulation or circular harmonic expansion coefficients are necessary [34].

The description of the acoustic scene by means of several individual sound sources enables the interactive manipulation of parameters. This is necessary for real-time adaptation of the sound field. Sound nodes are positioned spatially, together with the geometry of the corresponding machine components, in connection points between two components or in the inner of the components. Thus, the sound sources are automatically moved along with the movements of the geometry in the scene.



(a) Audio-visual VR-system at the KVR

(b) Loudspeaker wall at IDMT

Fig. 16. Audio visual reproduction of the virtual pick-and-place unit in two VR-systems. (a) VR-laboratory of the Ilmenau University of Technology. (b) audio visual VR-laboratory at IDMT.

5. APPLICATION

For the auralisation of the acoustical behaviour of the virtual product - here the pick-and-place unit - two novel VR-systems are used. An image of both systems is shown in figure 16. Figure 16 (a) shows the audio-visual CAVE (Cave Automatic Virtual Environment) [35] like setup installed at the Competence Centre Virtual Reality (KVR) of Ilmenau University of Technology. This VR-system (Flexible Audio-visual Stereoscopic Projection system (FASP)) combines stereoscopic projection and sound reproduction by means of the WFS method. The stereoscopic projection setup has three flexible projection walls, while two are movable. Degree of immersion and size of the FASP installation can be adapted depending on the application and number of users inside the VR-system. The condition for the reproduction of the sound field using the WFS method is to have a closed circle of loudspeakers around the listener area. The FASP installation has 208 loudspeakers. Further details about the system are explained in [36]. In figure 16 (b) the audio-visual VR-system at Fraunhofer Institute for Digital Media Technology (IDMT) is shown. The system uses a stereoscopic projection for visualisation of the virtual product on an acoustic permeable screen. Behind the screen a planar array of loudspeakers is situated, used for WFS. The image shows an user listening and watching to a virtual representation of the pick-and-place unit. While using the system, the virtual object can be rotated and translated interactively. The auralisation of the directional sound field is adapted continuously.

6. CONCLUSION

This contribution shows steps towards an integration of acoustical information to extended Virtual Reality environments. An approach was presented to assess the acoustical behaviour of technical products in the early phases of product development. Starting with the simulation of sound generation, a model leading to auralisation was shown. Parametric, simplified models are developed for some stimulation mechanisms for quasi-static states, which calculate the stimulation spectrum according to the design parameters of the product and its current state in real-time. In addition, measured sound spectra of real components are used. The simulation of structure borne sound transmission is based on a four-pole approach. In the next (and current) step it is important to develop product models parameterised in such a way that sound stimulation sources and transmission paths can be identified and modified in early development phases. Finally, these models have to be integrated into the (virtual) product development process and into the existing CAx landscape.

For the auralisation the spatial sound reproduction technique of Wave Field Synthesis was used. In the context of virtual product development WFS allows the reproduction of sound fields, spatial correct for multiple users. This allows the evaluation of acoustical product properties by multiple users, at it is common in real applications. To use the WFS technology, an extension to the synthesis of directional sound fields was proposed. The concept is based on a decomposition of a sound field, into its circular harmonics components. Therefore this approach can be combined with any acoustical simulation techniques, that deliver the sound pressure or velocity on a circle around the virtual object. To arrive at a more practical WFS synthesis operator, the theoretical approach based on the assumption of two-dimensional sound fields was extended to synthesise sound fields using secondary point sources. As the position of the listener, the virtual source and the secondary source is limited in common WFS-systems to be in the same reproduction plane, also the simulation of the directivity has only to be done for this plane.

For the integration of the acoustical product properties in the scene graph the use of circular harmonic coefficients was proposed. These coefficients can be processed directly out of the simulation or measurement result and can be stored as a property of a virtual object in the scene graph. With this acoustical approach the object-based concept of scene graphs can be extended in a very intuitive way.

Using the example of a pick-and-place unit, main modelling options - with regard to product models as well as simulation principles - are discussed. First results are encouraging, but further investigations are necessary in order to obtain models accurate enough for use in the product design stage.

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8. REFERENCES

[1] Otto von Estorff, Sergej Rjasanow, Mirjam Stolper, and Olgierd Zaleski, "Two efficient methods for a multifrequency solution of the Helmholtz equation," *Computing and Visualization in Science*, vol. 8, no. 3-4, pp. 159–167, 2005.

[2] Michael Vorländer, *Auralization: Fundamentals of Acoustics, Modelling, Simulation, Algorithms and Acoustic Virtual Reality*, Springer Verlag, Berlin Heidelberg, 2008.

[3] O. von Estorff, "Challenges in Technical Acoustics: What can be computed today," in *LS-DYNA Anwenderforum*. 2008.

[4] A. J. Berkhout, "A Holographic Approach to Acoustic Control," *The Journal of the Audio Engineering Society*, vol. 36, no. 12, pp. 977–995, 1988.

[5] P. Vogel, *Application of wave field synthesis in room acoustics*, Ph.D. thesis, Delft University of Technology, Delft, The Netherlands, 1993.

[6] Evert Start, *Direct Sound Enhancement by Wave Field Synthesis*, Ph.D. thesis, Technische Universiteit Delft, 1997.

[7] Helmut Wittek, *Perceptual Differences between Wavefield Synthesis and Stereophony*, Ph.D. thesis, University of Surrey, 2007.

[8] Sascha Spors, *Active Listening Room Compensation for Spatial Sound Reproduction Systems*, Ph.D. thesis, University of Erlangen-Nürnberg, Erlangen-Nürnberg, 2007.

[9] Jens Ahrens and Sascha Spors, "Implementation of Directional Sources In Wave Field Synthesis," in *Applications of Signal Processing to Audio and Acoustics, 2007 IEEE Workshop on*, pp. 66–69. 2007.

[10] Leo L. Beranek, *Acoustics*, American Institute of Physics, Inc, 1 edition, 1993.

[11] Jens Ahrens, Rudolph Rabenstein, and Sascha Spors, "The Theory of Wave Field Synthesis Revisited," in *124th Convention of the Audio Engineering Society*, 2008.

[12] David T. Blackstock, *Fundamentals of Physical Acoustics*, John Wiley & Sons, Inc, 1 edition, 2000.

[13] Christoph Sladeczek, Michael Rath, Matthias Peine, and Sandra Brix, "On the Effect of Modal Aliasing in the Reproduction of Sound Fields of Directional Sources," in *18th International Congress on Sound & Vibration (ICSV18)*, Ricardo E. Musafir, Ed., 2011.

[14] Edo Hulsebos, *Auralization using Wave Field Synthesis*, Ph.D. thesis, Delft University of Technology, Delft, The Netherlands, 2004.

[15] *DIN 1311-1 Schwingungsfähige Syteme - Begriffe, Einteilung*, Deutsche Norm. Beuth, Berlin, 1994.

[16] Torsten Zschieschang, *Schwingungsanalyse an Maschinen mit ungleichförmig übersetzenden Getrieben*, Ph.D. thesis, Technische Universität Chemnitz, Chemnitz, 2000.

[17] T. H. Alber, B. M. Gibbs, and H. M. Fischer, "Characterisation of valves as sound sources: structure-borne sound," *Applied Acoustics*, vol. 70, no. 5, pp. 661–673, 2009.

[18] Stephan Husung, Tobias Kästner, Christian Weber, Günter Höhne, and Torsten Brix, "Simulation of acoustical product properties in early phases of the design process," in *International Design Conference*, D. Marjanovic, M. Storga, N. Pavkovic, and N. Bojcetic, Eds. 2010, vol. 11, pp. 1343–1352, Design Society.

[19] Jeroen Anton Wensing, *On the dynamics of ball bearings*, Ph.D. thesis, University of Twente, Enschede, 1998.

[20] Joao Henrique Diniz Guimaraes, *Modelling the dynamic interactions of rolling bearings*, Ph.D. thesis, Rheinisch-WestfÂ¨alische Technische Hochschule Aachen, Aachen.

[21] Daniel Bader, *Entwicklung einer flexiblen akustischen Messmethode zur Detektierung von verzahnungstechnischen Qualitätsproblemen*, Ph.D. thesis, Tehnische Universität Ilmenau, Ilmenau, 2007.

[22] Ferit Küçükay, *Dynamik der Zahnradgetriebe: Modelle, Verfahren, Verhalten*, Springer-Verlag, Berlin, New York, 1987.

[23] Hiroyuki Ohta and Eiji Hayashi, "Vibration of linear guideway type recirculation linear ball bearings," *Journal of Sound and Vibration*, vol. 235, no. 5, pp. 847–861, 2000.

[24] Hans Dresig, *Schwingungen mechanischer Antriebssysteme: Modellbildung, Berechnung, Analyse, Synthese*, Springer, Berlin, 2. edition, 2006.

[25] Bernd Wender, "Untersuchungen zur Gehäusegestaltung für lärmarme Zahnradgetriebe," *Konstruktion*, vol. 6, pp. 85–90, 2002.

[26] Silje Korte, *Untersuchung der hochfrequenten akustischen Transmission einer Kfz-Bodengruppe mittels Statistischer Energieanalyse*, Ph.D. thesis, Techniche Universität Berlin, Berlin, 2005.

[27] Dietmar Findeisen, *System dynamics and mechanical vibrations. An Introduction*, Springer, Berlin [u.a.], 2000.

[28] Christian Weber, "Simulationsmodelle für Maschinenelemente als Komponenten mechatronischer Systeme," in *Internationales Wissenschaftliches Kolloquium*, Peter Scharff, Ed. 2005, pp. 605–606 (Executive Summary), Verl. ISLE.

[29] Rüdiger G. Ballas, Günther Pfeifer, and Roland Werthschützky, *Elektromechanische Systeme der Mikrotechnik und Mechatronik. Dynamischer Entwurf - Grundlagen und Anwendungen*, Springer, Berlin [u.a.], 2. edition, 2009.

[30] Otto von Estorff, Marian Markiewicz, Ralf J. May, and Olgierd Zaleski, "Sound Radiation of a Gear Box Using Acoustic Transfer Functions," in *Tagung der Arbeitsgemeinschaft für Akustik DAGA*, vol. 30, pp. 3–4. 2004.

[31] Otto von Estorff and Olgierd Zaleski, "Efficient acoustic calculations by the BEM and frequency interpolated transfer functions," *Engineering Analysis with Boundary Elements*, vol. 27, no. 7, pp. 683–694, 2003.

[32] Stephan Husung, Michael Reeßing, Christian Weber, and Anita Tröbs, "Verhaltensmodellierung technischer Systeme für audio-visuelle VR-Anwendungen," in *9. Paderborner Workshop Augmented & Virtual Reality in der Produktentstehung*, Jürgen Gausemeier and Michael Grafe, Eds., HNI-Verlagsschriftenreihe, pp. 143–156. 2010.

[33] *ISO/IEC 14772-1: Information technology - Computer graphics and image processing - The Virtual Reality Modeling Language - Part 1: Functional specification and UTF-8 encoding*, Deutsche Norm. 1997.

[34] Günter Höhne, Stephan Husung, Torsten Brix, Eberhard Lotter, and Sandra Brix, "Virtual Prototyping of technical products using a new audiovisual VR system," in *19th International Congress of Mechanical Engineering*, Brazilian Society of Mechanical Sciences and Engineering, Ed., 2007.

[35] Carolina Cruz-Neira, Daniel J. Sandin, Thomas A. DeFanti, Robert V. Kenyon, and John C. Hart, "The CAVE: audio visual experience automatic virtual environment," *Communications of the ACM*, vol. 35, no. 6, pp. 64–72, 1992.

[36] Günter Höhne, Stephan Husung, Eberhard Lotter, and Christian Weber, “Virtuelle Produktentwicklung unter Nutzung eines audiovisuellen VR-Systems,” *Konstruktion*, vol. 10-2009, no. 61, pp. 52–58, 2009.