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SIMULATION OF ACOUSTICAL PRODUCT PROPERTIES IN EARLY PHASES OF THE DESIGN PROCESS

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1. Introduction

Today, product development is dominated by reducing time and costs, 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 optimisation before first physical prototypes are built. Representing simulation results by use of (extended) Virtual Reality (VR) technologies has advantages – especially if both the simulation tools and the VR representation are multimodal (e.g. in our case: 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. Using intuitive interaction tools, the user can navigate in the VR scene, manipulate and investigate the scene content.

This paper deals with introducing extended, i.e. audio-visual VR technologies into the product development process. It will be shown that, in order to provide product models fit for design purposes, first some intensive basic research questions have to be solved. In this respect, the focus on audio-visual representations is an example for any case of multimodal VR – often overseen by VR approaches coming from computer science.

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 behaviour (e.g. motion = geometry changes in time) can be transferred. The spectrum of the perception should be extended, because nowadays for the acceptance and the understanding 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 for technical application, thus adding to the kind and number of product properties that can be assessed and optimised in early phases (i.e. “virtual” instead of “physical” stages) of product development.

In many cases, product development has to take into account the acoustic behaviour of technical systems. 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 spectrum 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. for motor cars, motor bikes, household machinery …).

All this is, at present, mostly done by experience and trial-and-error. Often clear statements about the acoustical behaviour of a product are only possible after manufacturing first prototypes.

In the work presented here, the goal is to include acoustic analysis and synthesis in the early phases of engineering design process by means of virtual prototyping. The vision is to auralise the acoustical product properties based on a virtual prototype to enable an acoustic evaluation and optimisation. The overall concept and vision is illustrated in figure 1. The product development engineer needs methods, models and tools to simulate the acoustical behaviour based on the current product characteristics.

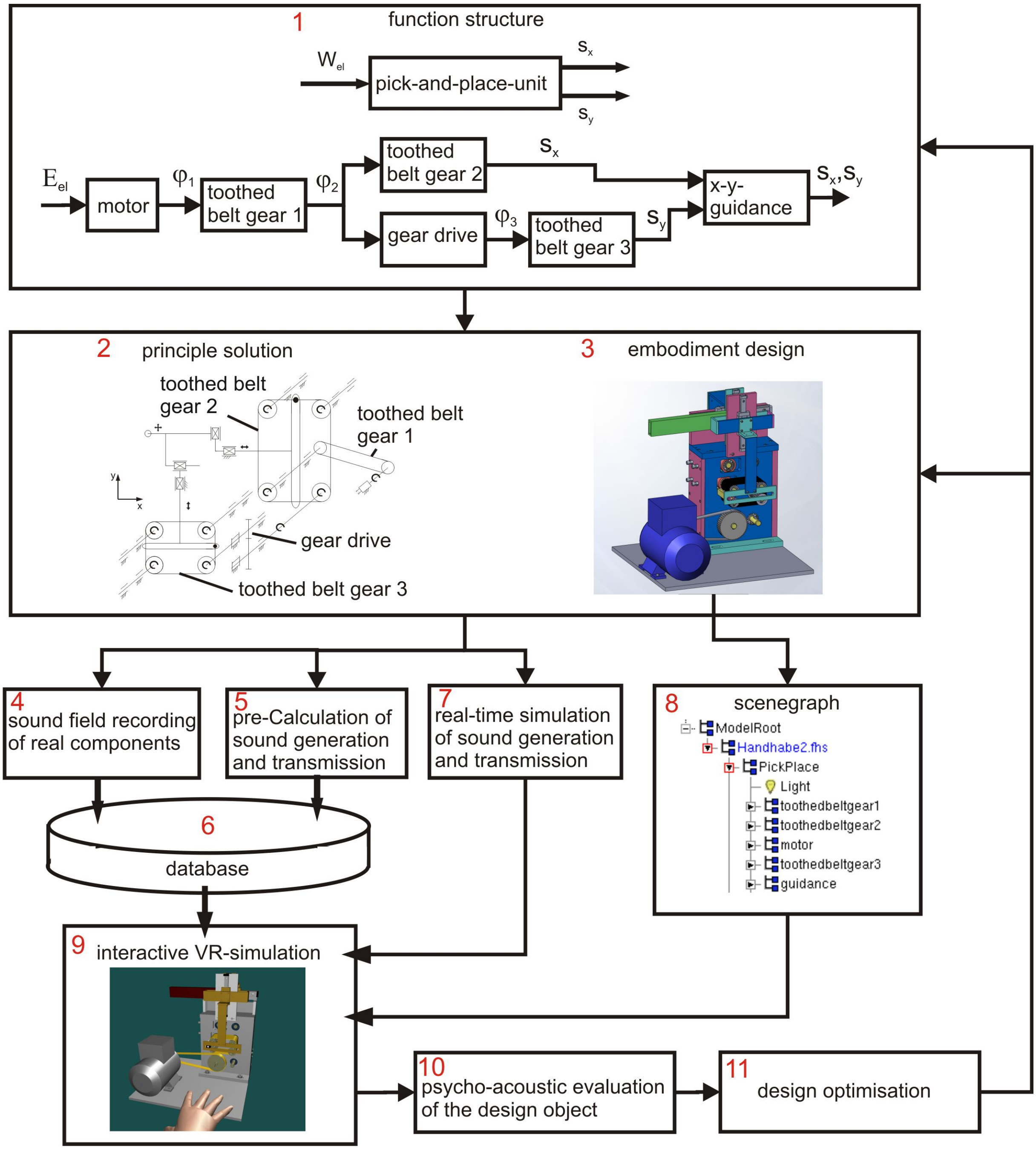

Figure 1. Overall concept for integration audio-visual VR in product development process

For audio-visual investigations in VR two pre-requisites have to be fulfilled:

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

This contribution discusses the use of the audio-visual VR-system and the necessary simulation methods and models required for product development. This is explained via the example of a pick-and-place unit. The task of the specific design process is to develop a two-coordinate pick-and-place unit for assembling purposes with short cycle times and a low noise level. The design process follows as

shown in figure 1 the well known procedure developing for the overall function a function structure, one (or more) principle solution and a preliminary embodiment design.
The unit generates a two-coordinate motion of the output bar by two toothed belt gears, driven by an electric motor. The generated noise is subject of this investigation. The main focus of the investigation is the real-time simulation of the sound generation and transmission through the structure. The goal is to represent and present the acoustical product properties for real-time auralisation in the VR-system and to provide means for their optimisation by modifying the system parameters.

2. Initial Work

A novel VR system was erected at the Competence Centre Virtual Reality of Ilmenau University of Technology (figure 2). This is a flexible 3-screen stereoscopic projection system for visualisation in combination with spatial sound presentation based on the wave-field-synthesis (WFS) [BBS04] principle. This installation with 218 separately controlled speakers is able to generate a realistic spatial sound field with correct representation of the sound sources position and loudness.

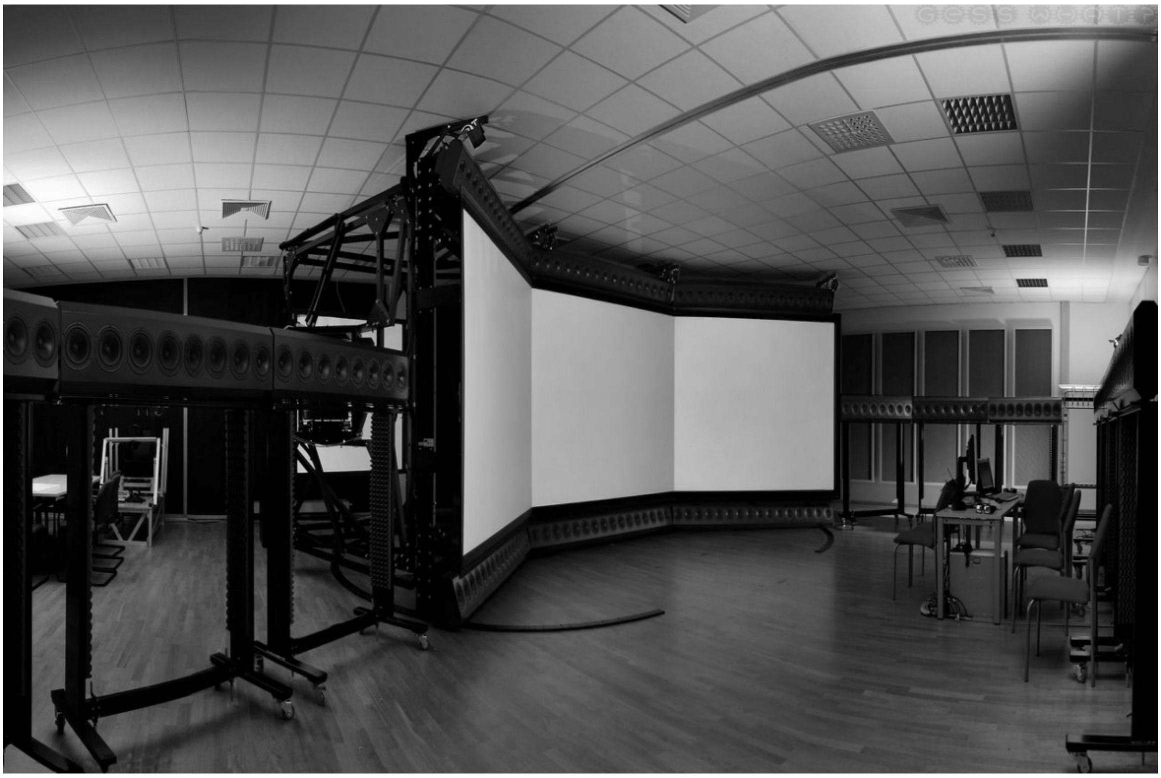

Figure 2. Audio-visual VR-system at the Competence Centre Virtual Reality

3D-CAD models are the basis for generating the geometrical VR representations and the functional modelling of the respective systems. In order to represent acoustical information in the virtual product model, the VR scene graph was enhanced by special VRML-nodes, which contains acoustic parameters like the spatial position of sound sources and their (relative) volumes. For the wave-field-synthesis (WFS) representation several other parameters like distance-dependent loudness or sound emission angle for plane waves are necessary (see figure 3) [HHBL07].
The description of the acoustic scene by means of several individual sound sources enables the interactive manipulation of parameters, which is necessary for real-time adaptation of the sound field. Audio nodes are positioned spatially, together with the geometry of the corresponding machine components, in connection points between two components or, in the case of more complicated devices and machines, on their surfaces. Thus, the sound sources are be moved automatically according to movements of the geometry in the scene.

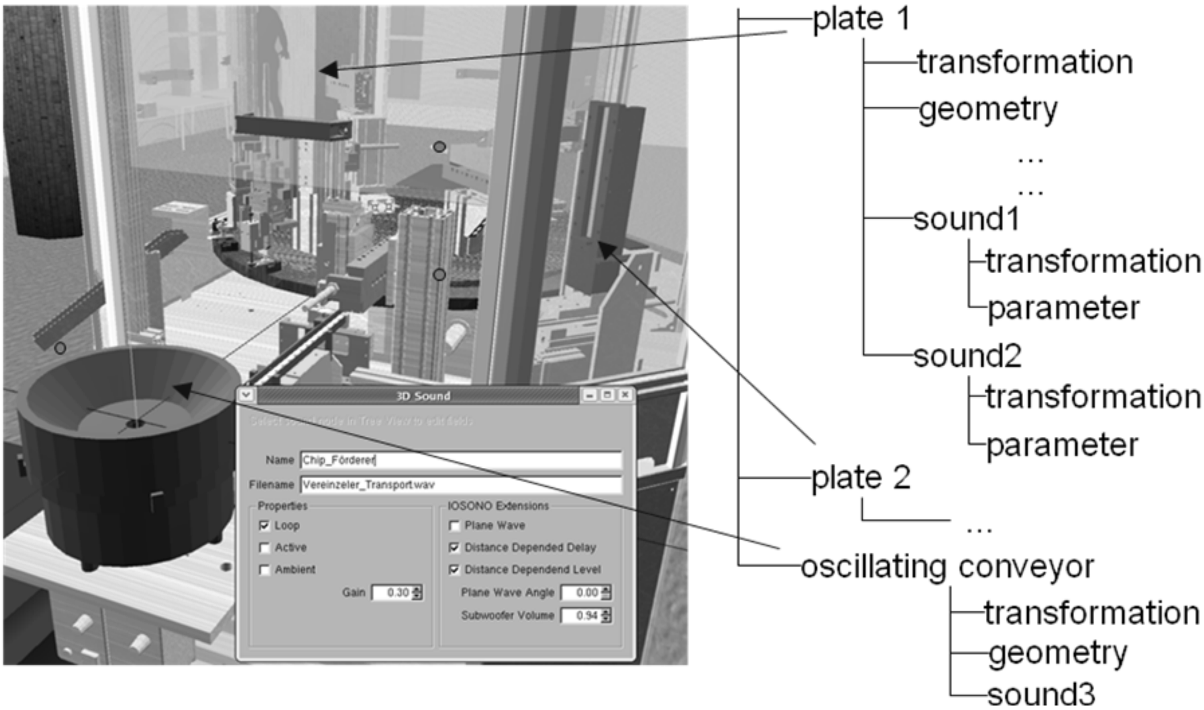

Figure 3. Audio-visual model of a revolving automatic assembly machine

Real components have a sound radiation which is more complicated than simple (punctiform) audio nodes. Hence, as a 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 4 shows the main portals of a revolving automatic assembly machine. The main user of the audio-visual VR installation is head-tracked; if the user 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. A second approach was developed by substituting the real sound source and its directional radiation by a number of (punctiform) monopole-sources [Gi96; HWG09]. The big advantage of the second approach is a good reproduction of the directional characteristic around the system without subdivision into portals; the disadvantage is the quite big number of individual sound sources.

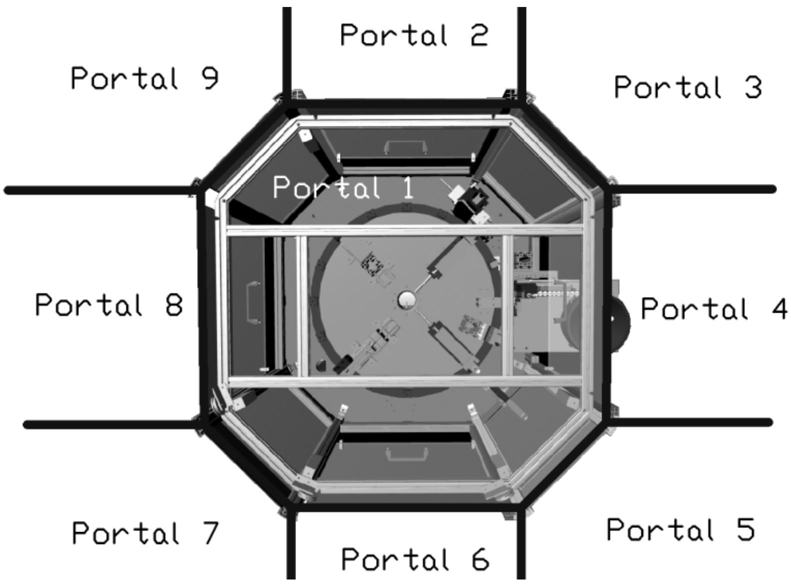

Figure 4. Portals in the model of a revolving automatic assembly machine

The first models briefly described in this section were entirely based on empirical, i.e. measured data of existing components (see figure 1, block 4, 5, 6). 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 needed for further research.

3. Simulation of Acoustic Properties

To simulate the acoustical behaviour the model has to represent the acoustical properties for a real-time auralisation and has to enable a modification of the relevant design characteristics (geometry, material ...) for improving the acoustical product quality.
There exist several investigations [DS05; Ko00; WWH99] in modelling parts of sound propagation. But currently there is no final set of modelling methods and tools for the sufficiently realistic precalculation of acoustic product properties for auralisation in VR.
The following sub-sections of this chapter discuss the main steps of modelling the sound propagation chain in VR for the example of a pick-and-place unit which mainly consists of typical machine elements (bearing, gear drive, toothed belts, guidance ...) and which is mostly made of metal.

3.1 Sound propagation chain

Hearable sound is a vibration in the frequency range of 20 … 20,000 Hz. Depending on the transmitting medium, sound is differentiated in structure-borne, fluid-borne and air-borne sound. The sound which is directly hearable 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. For realistic reproduction the sound propagation chain (figure 5) has to be realised also in the VR simulation.

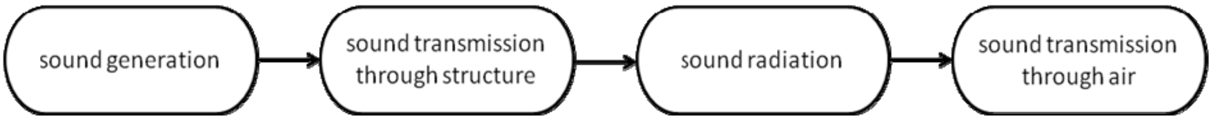

Figure 5. General sound propagation chain

3.2 Sound generation

The first step is to identify the relevant noise sources in the product structure. The main physical mechanisms of sound/noise generation are shock between components, sequence of shocks, friction and inside the components variations of characteristic parameters (like stiffness) and mass-forces. Sound stimulation can also be caused by technological processes or modulated functions of the position excited by the actuator or gearbox.
Analysing the principle solution and the embodiment design (figure 1) in the pick-and-place unit are found the following noise sources:

- 16 ball-bearings
- 3 toothed belt gears with 10 toothed belt discs
- 1 gear transmission
- 3 linear guidances with recirculating linear ball bearings

In literature several models for the stimulation mechanisms can be found [DS05; Ko00; WWH99]. The main stimulations of ball-bearings are the radial stiffness variation during rotation and deviations of the balls or rings from their ideal geometry. For a gear transmission the main mechanism are variations of the teeth stiffness during meshing, deviations of the tooth forms and surfaces and mass forces because of angular accelerations. For the calculation of the amplitudes at the stimulation frequencies geometrical parameters can be used and the kinetic or dynamic state has to be considered. With the goal to manipulate the acoustical behaviour the model should be parameterised.
The investigation shows that many stimulation mechanisms can be modelled with simplified models. Main obstacle is, however, the modelling of the friction process, which leads to non-realistic results if

performed with current mathematical models. In the pick-and-place unit this occurs when modelling the linear guides which are of the recirculating ball type. The main stimulation frequencies are based on rolling natural vibration, yawing, pitching and bouncing [OH00]. They depend on the geometrical parameters. For many machine-acoustic investigations the modelling of this stimulation frequencies is sufficient. But for acoustic investigation with an auralisation of the acoustical behaviour the stimulate frequencies by means of friction have to be considered. In our investigation therefore empiric data was used.

3.2 Sound transmission

The basic equation to calculate structure-borne sound transmission, i.e. propagating sound 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 behaviour (e.g. FEM) is currently not possible in real-time or could not consider all relevant frequencies (e.g. SEA). 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) [Vor08]. 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 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.

In the area of electrical networks another method was found: Each component is described as a two-port or four-pole [Fin00]. 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. In the following section the term four-pole (see figure 6) is used.

The four-pole approach can be used to establish multi-domain (e.g. mechatronics) behaviour models of systems. 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 6.

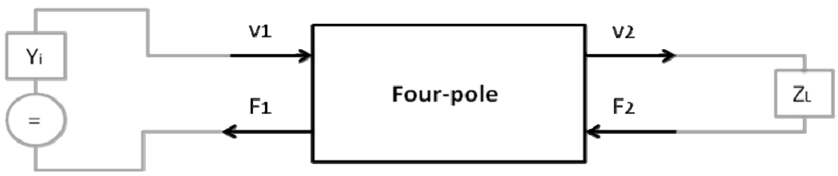

Figure 6. Simple four pole with a source and a load impedance

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

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

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.

The coefficients 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 (figure 7).

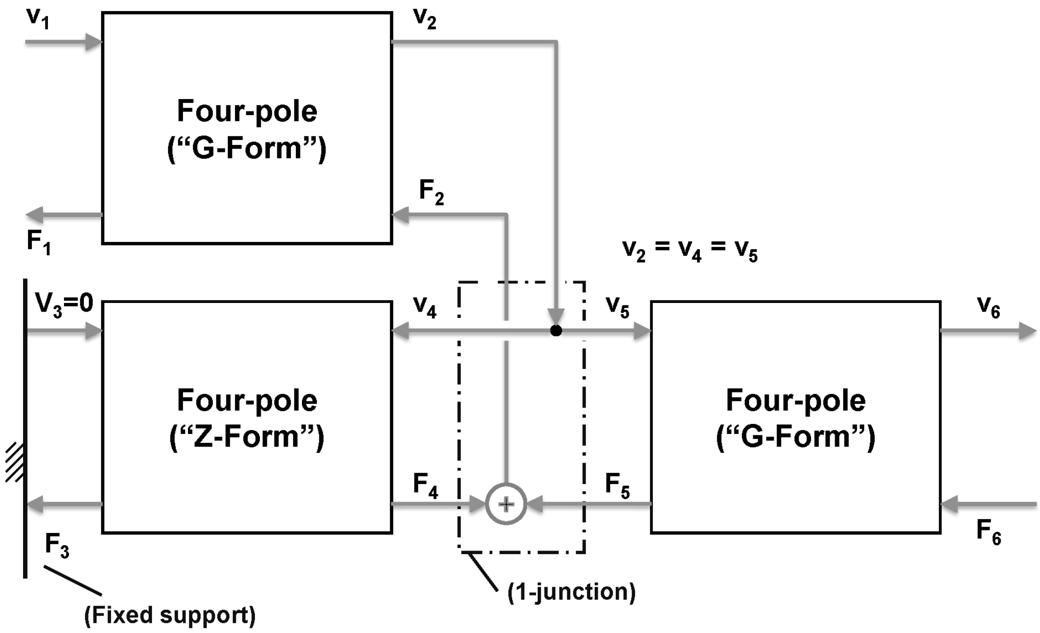

Figure 7. Coupling of four poles

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 like shafts, are, however, simulated using vibration differential equation. So a direct influence on the mechanical parameters is possible.
The measured four-pole parameters are frequency-depended vectors. Usually, they contain no direct link to the design parameters of the component or product, so are of limited value for the development engineer. For the modification of the transmission the four-pole parameters gained from measurements have to be parameterised.
In the project this was done by polynomial interpolation and transforming the transfer function in residue form. Using the residua the modal parameters of the system can be detected.

$$H_N(\omega) = \sum_{r=1}^{k} H_r(\omega) = \sum_{r=1}^{k} \frac{R_r}{j\omega - p_r} + \frac{R_r^*}{j\omega - p_r^*} \tag{3}$$

A measured and reproduced transfer function with modal parameters for the four-pole parameters is shown in figure 8. Modifications on the acoustic transmission are possible in a limited range based on the parameterised transfer function and the four-poles. The engineer can change the mass, the stiffness or the damping factors by modification of the detected modal parameters.
The results of the acoustic transmission simulation are velocity vectors at discrete points on the surface. This information can be used for the simulation of the sound radiation, what is not explained in this paper.

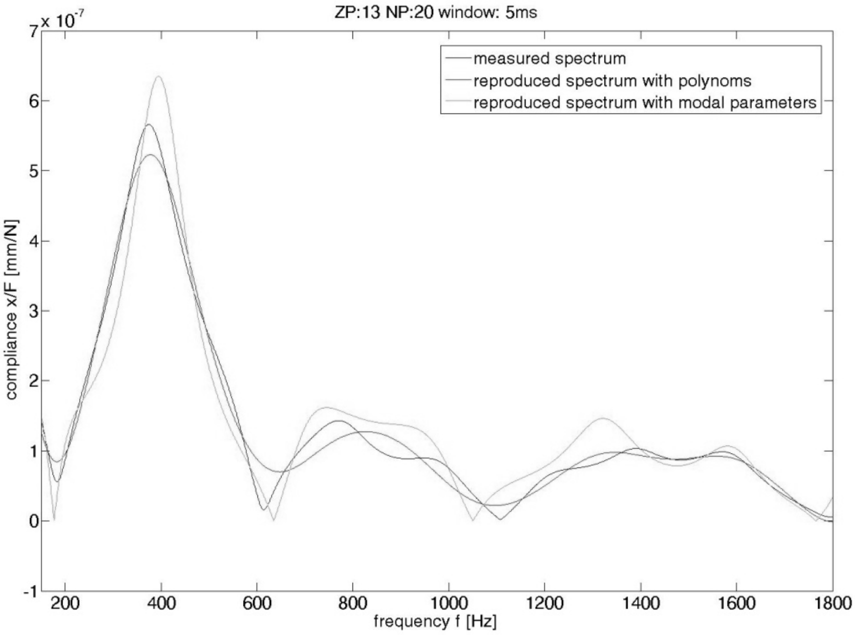

Figure 8. Measured and reproduced transfer function

The presented simulation methods were used to simulate the pick-and-place unit (figure 9) by modelling the separate components (gears, bearings, shafts, enclosure …) and liking them to a network. This modular concept of the complied sound modelling enables the designer to reuse the models for other applications.
A prototype was built to verify the calculation results (see figure 9).

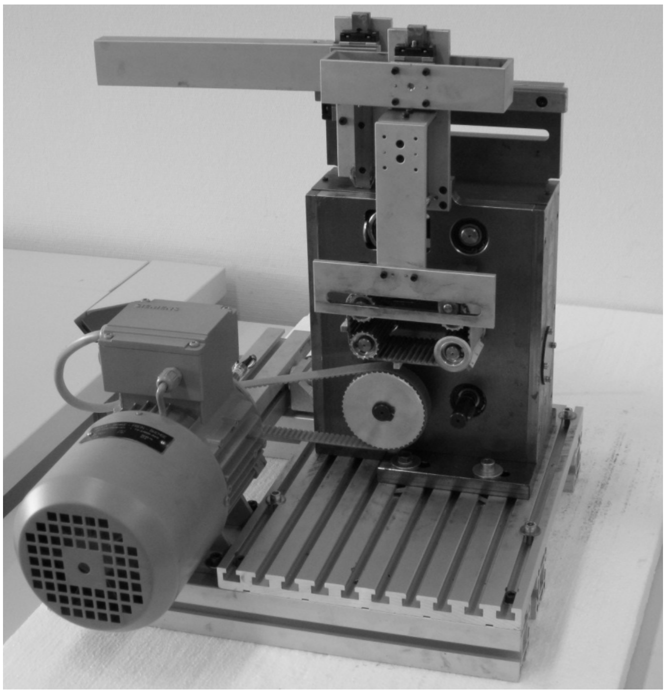

Figure 9. Pick-and-Place Unit

Figure 10 shows the measured (left) and simulated (right) acceleration on the side wall of the machine. The results show that the main sound characteristic is represented well (i.e. close to reality). The main peaks in the spectrum are produced by the non-steady state of the linear guides.

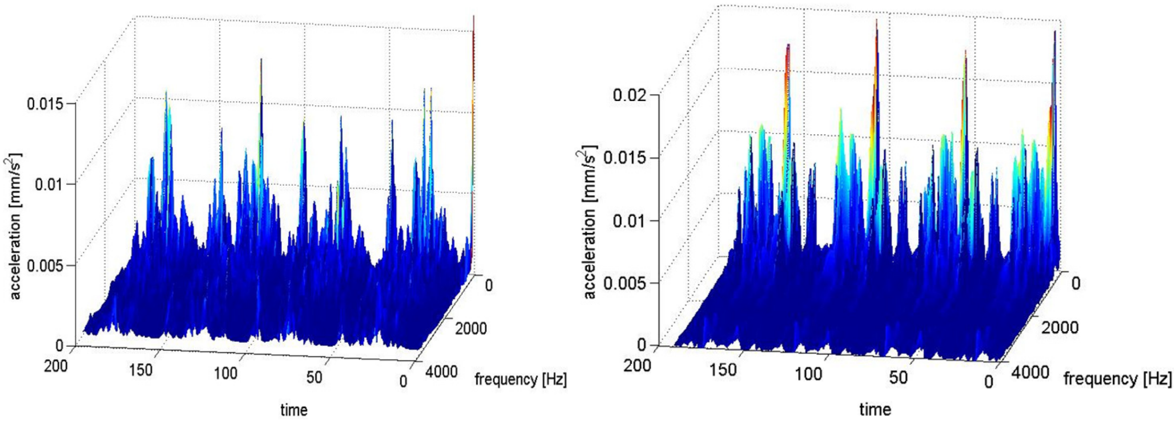

Figure 10. Measured and simulated acceleration on the surface (side wall) of the pick-place unit

4. VR Representation and Design Review

After the model preparation, the interactive real-time simulation, the psycho-acoustic assessment and necessary modifications of design object are the final tasks of the process (figure 1, blocks 9, 10, 11) with the goal to optimize the acoustic behaviour of the product.

The reproduction of the sound field in the audio-visual VR-system permits acoustic observation of the overall pick-and-place unit in different directions. So the user is able to find portals with high and low noise level.

All sound sources are manipulable separately. By switching them off and on virtually the influence of every component or group on the overall noise radiation can be recognized and noise critical components identified.

Also parameters of the model (stimulation and transmission) can be changed easily, many of them during the simulation runtime. The advantage for the design process is the possibility to find dominating sound stimulation sources and transmission paths.

The vision is to provide the engineer substantiated information for determined optimisation:

- substitution of components (e.g. ball-bearings → sliding bearings)
- exchange of components (e.g. vociferous machine elements by low-noise once)
- exchange of materials
- variation of noise relevant parameters (stiffness, mass, roughness,..) by modification of shape, dimensions and tolerances
- insertion of damping means
- insulation, shielding of noise
- etc.

With the modified structure the simulation starts again up to a sufficient acoustic behaviour.

5. Conclusion

The work presented in this contribution shows first steps towards an assessment of the acoustical behaviour of technical products in early phases of product development. As the results shall be presented in an audio-visual VR environment, real-time simulation is a serious issue. 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 product development.

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 (i.e. development phases. Finally, these models have to be integrated into the (virtual) product development process and into the existing CAx landscape.

Acknowledgment

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