TOWARDS THE AURALIZATION OF ELECTRICAL MACHINES IN COMPLEX VIRTUAL SCENARIOS

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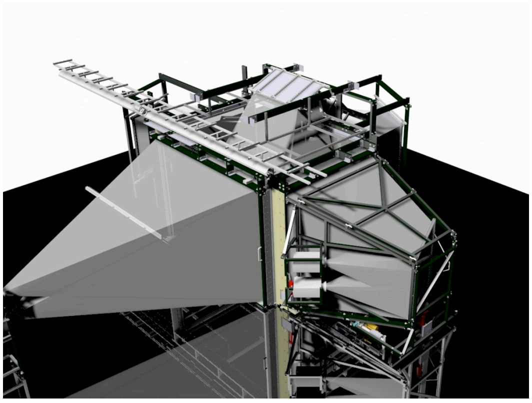
ABSTRACT

In industrial work environments electrical machines are used in various applications and are often perceived as annoying acoustic sources. Their auralization in realistic environments allows to assess the sound quality and to develop acoustically optimized machine designs and controls. Virtual reality combining 3-D visualization and binaural sound reproduction enables designer and user to fully immerge into the application scenario. Efficient computation of the radiated sound field at arbitrary torque/speed points is required. This work proposes a general concept for fast auralization interfacing electromagnetic force excitation, structural-dynamic response, radiation patterns and binaural perception.

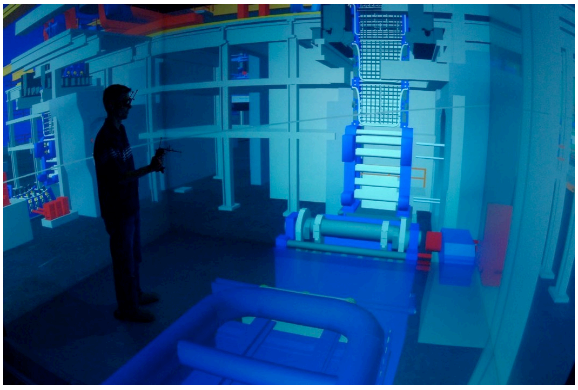
INTRODUCTION

At RWTH Aachen University a cave-like environment has been established in July 2004 in the Virtual Reality Center Aachen (VRCA) and is being successfully used by many institutes for various applications [6]. The system, as shown in Figure 1, uses four side walls and the floor for video projection. The stereoscopic projection is achieved by two individual projectors for each surface. Users can immerge into the visual virtual reality by wearing special eyeglasses. The position and orientation of the user's head is determined by a camera system.

At the top of the side walls four loudspeaker are mounted in the edges and build the sound reproduction system using crosstalk-cancelation (CTC) technique. Therefore, the user perceives binaural signals and can immerge into a 3D acoustic scene without wearing additional headphones. The acoustic scene is rendered in real-time using a highly optimized convolution engine and a combination of image-source and ray-tracing techniques for the simulation of room impulse responses [4].



(a)



(b)

Figure 1: a) View of the CAVE-like environment at RWTH Aachen University. Dimensions: 3.6x2.7x2.7 m^3. b) User interacting with a virtual scenario of a manufacturing platform inside RWTH Aachen CAVE-like environment (taken from [6]).

For this particular system various 3D scenes have already been programmed but they mostly concentrate on the visual part as e.g. the manufacturing hall shown in Figure 1(b). These scenarios are already of high complexity and have to be acoustically modeled by many separate sound sources. The sound generation, transmission and the room influence have to be calculated for each source individually in order to obtain a plausible acoustic impression. As recent research developed techniques to include the radiation pattern of acoustic sources into the system, the basis for complete virtual prototyping of machines and realistic and interactive psycho-acoustic studies, before the actual manufacturing of a prototype, is given. The system is already capable to auralize such complexity in real-time if source signals and radiation pattern are available. Hence, the task remains to simulate the source signals and radiation patterns. Simulations of the electrical fields, structural dynamics and the radiation pattern require computational intensive calculations and cannot be done in real-time. This paper proposes a modularized concept to calculate binaural signals of a running electrical machine in a realistic environment of a machinery hall to optimize the computation time.

CONCEPT

The proposed concept strictly separates between calculations to done during the phase when the user interacts with the scene (online) and calculation to bo done prior to the use (offline). The aim is to achieve real time capability by doing as little processing online as possible and pre-calculating the block behavior. All computational expensive simulations are processed offline. A finite number of conditions is simulated and intermediate conditions are interpolated. The granularity is determined by the desired psychoacoustic quality. The final results are synthesized based on this data. The four blocks of the block diagram as shown in Figure 2 are meant to be independent of each other and can be described in terms of transfer functions. Suitable interfaces, typically based on physical quantities, are defined. Inputs to the force excitation calculation are torque T and speed n. The resulting excitation forces *X* form the link to the structural simulations which then output the surface velocity v_S. This quantity is used to calculate the free-field radiation pattern in terms of sound pressure p and particle velocity v. Finally, room simulations yield the binaural pressure signals p_bin including the room. Inside details of the first three blocks are given in the following sections. The room simulation is not further explained here. It is, for example, already used for the auralization of musical instruments in concert halls. This concept of modularization and independent calculation is also followed inside the room acoustic simulation software *RAVEN*, where *portals* are used to define interfaces between different rooms [9] which can be simulated independently.

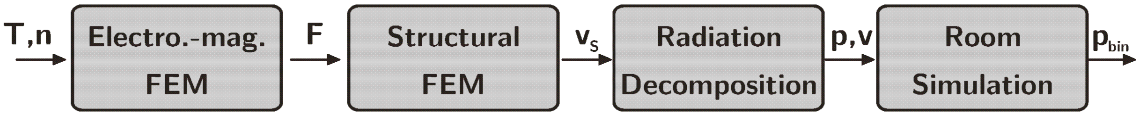


Figure 2: Block diagram of the proposed concept including physical quantities used to exchange processed data.

FORCE EXCITATION

In industrial applications, the most common electrical machines are induction machines and synchronous machines complemented by DC machines for miniature drive systems and switched reluctance machines for high speed applications. A tonal sound with a strong and disturbing high frequency content is common to most electrical machines. The acoustic spectrum of synchronous machines is often dominated by the frequency component equal to the number of stator slots multiplied by the mechanical speed. In switched reluctance machines the multiples of the number of rotor teeth times the mechanical speed are the main noise components. In induction machines, the interaction is more complex. However, early on tables have been developed which allow to look up the main exciting frequencies [3].

In the air gap between stator and rotor of an electrical machine, electrical power is converted into mechanical power and vice versa. Forces act on the air gap surface of stator and rotor. The constant component of the tangential force represents the desired torque while all fluctuating components of both radial and tangential force are a byproduct and a potential source of acoustic noise. Figure 3 shows a snapshot of the force acting on a stator pole of a synchronous machine.

Electromagnetic force can be calculated using analytical methods or numerical field computations. The latter one is nowadays typically used due to the greater accuracy. One method of numerical field computation is the finite element method (FEM) [11]. In principle, it can be used in two dimensions, or in three dimensions. To keep the computational effort as low as possible, 2D-methods are used whenever possible. If, for example the electrical machine is homogeneous in axial direction, 2D electromagnetic FEM can be used, if e.g. the rotor is skewed multiple 2D calculations are still more efficient than a complete 3D approach [2].As the structure of the electrical machine typically exhibits a 3D nature, the structural dynamic simulation is performed using 3D models. Therefore, the 2D forces are transformed to the 3D structural model [10].

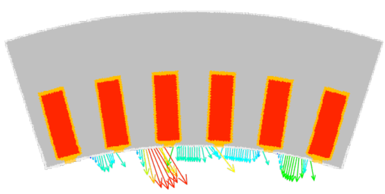


Figure 3: Snapshot of force on stator.

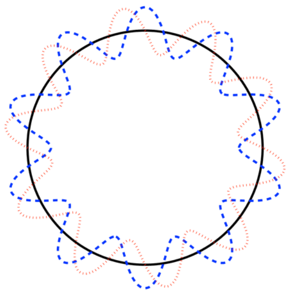


Figure 4: Schematic representation of the mode 0 excitation shape.

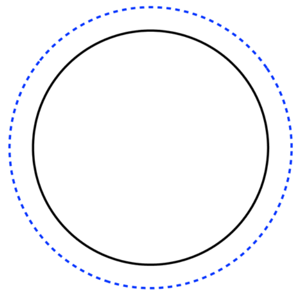


Figure 5: Schematic representation of the mode 10 excitation shape.

For analysis as well as for use in auralization the force is decomposed in the spatial and in the temporal domain. A schematic representation of the excitation shape of a mode 0 and a mode 10 (spatial decomposition) is given in Figures 4 and 5. Lower order modes in the force occur, for example, if the machine has a lower number of pole pairs of if the machine is eccentric.

In general, the force distribution $f_{d,M}(\alpha)$ in N/m along the air gap is described by the superposition of excitation modes m up to the M^{th} spatial component as

$$f_{d,M}(\alpha) = \sum_{m=0}^{M} \left(a_{d,m}(t) \cdot \cos(m\alpha) + b_{d,m}(t) \cdot \sin(m\alpha) \right) \tag{1}$$

where α is the angle of a location in the air gap. Index d denotes the direction, i.e. radial ('r') or tangential ('t'). Here, the force is assumed to be constant in the axial direction with no axial component. The time dependent amplitude factors $a_{d,m}(t)$ and $b_{d,m}(t)$ are decomposed into their complex frequency components $A_{d,m}(f)$ and $B_{d,m}(f)$ [1]. These coefficients as a function of torque T and speed n operating points are the force input to the auralization process. They are calculated offline for the entire operation range. The likewise offline calculated structural and radiation transfer functions (cp. next sections) are then scaled according to the chosen operating point in real-time.

STRUCTURAL-DYNAMIC SIMULATION

Based on the surface force density acting on the stator teeth obtained by the electromagnetic simulation, a structural-dynamic calculation is performed to determine the transfer functions from the radial force modes to the surface velocities,

$$V = H \cdot F\,. \tag{2}$$

Each element of the vector F represents the spectrum of one radial force mode, each element of the vector V is the spectrum of the velocity at one point on the machine surface. Hence each element of the matrix H represents one transfer function and the entire matrix describes the structural behavior sufficiently.

For complex structures, such as electrical machines, the finite element method is usually applied for the calculation of such transfer functions. Thus a three-dimensional model of the complete mechanical structure is built. The deformation of the stator can be represented as the displacement of each node of the mechanical finite element model summarized in the vector D. This leads to the matrix formulation of the equation of motion:

$$KD + C\dot{D} + M\ddot{D} = F \tag{3}$$

where the vector F represents the exciting forces at the nodes of the model, K the global stiffness matrix, M the mass matrix, and C the damping matrix. Due to the spectral composition of the exciting force waves, see section *Force Excitation*, the equation of motion can be evaluated for single frequencies as a harmonic analysis, which simplifies the calculation of the derivation:

$$D(K + j\omega C - \omega^2 M) = F \tag{4}$$

Since the exciting forces consist of only a few frequencies, such a harmonic analysis greatly reduces the computational effort compared to a transient analysis. A further reduction can be achieved by using modal superposition, compare [8]. In a first step, the eigenfrequencies (eigenvalues) and eigenmodes (eigenvectors) of the structure are calculated. By considering only the eigenfrequencies within the acoustic range, eq. 10 can be transformed so that finally only one mass-spring-damper problem has to be solved per eigenmode. To effectively combine harmonic analysis and modal superposition, many finite element tools allow for a clustering of the investigated frequencies around the eigenfrequencies instead of using a fixed interval. That way, the required number of computations can be kept as low as possible.

Performing such an analysis for an excitation of the structure with one of the spatial force modes with the amplitude 1 N yields one element of the matrix H from eq. 8. Thus it takes some time to compute the entire matrix. But all these calculations can be done prior to the real time virtual reality simulation. The transfer functions are then stored in look-up tables and during run-time a simple multiplication with the exciting force mode magnitude and phase is sufficient to determine the surface velocities, which are the input signals for the radiation calculation.

AURALIZATION

Based on the surface velocity the radiation pattern of the machine has to be calculated. This can be done using different approaches. The boundary element method (BEM) allows calculating the radiation of an arbitrary vibrating surface, which has to be sampled spatially on a sufficient dense mesh. These discrete surface velocity values are used to compute the sound pressure at any arbitrary distance. The BEM is a computationally expensive method and requires a large amount of memory. As for a realistic auralization the machines have to be simulated in many different running conditions and frequency ranges (cf. section *Concept*), the total computation time required can be very high. Alternatively, auralization can be done by decomposing the surface velocity into a weighted set of orthonormal base functions. Depending on the geometry of the vibrating body, cylindrical or spherical harmonics can be used as suitable base functions. The total surface velocity can then be expressed as a superposition of these base functions weighted with the calculated coefficients. Spherical harmonics have already been used to investigate radiation patterns of musical instruments by Pollow et. al. [7].

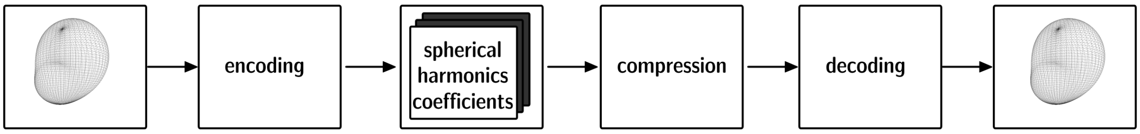


Figure 6: Encoding of the directivity in terms of spherical harmonics coefficients to reduce memory usage.

As the lower order coefficients dominate the far-field radiation of the vibrating object, the computation time and memory requirements can be reduced significantly by deleting coefficients of higher order and/or very low energy. Furthermore, the far-field radiation of the used base functions for the surface velocity can be pre-computed. A change of the surface velocity thus results in an inexpensively calculated change of coefficients, which then can be used to gain the far-field radiation by simple superposition. Drawback of this method is the constraint to cylindrical or spherical objects. In practice, however, such an approximation is usually acceptable as the lower order coefficients (small spatial change) are dominant for the far-field radiation.

SUMMARY

A concept for modularization of the entire auralization process of an electrical machine inside a working hall was presented. Real-time constraints led to pre-processing of time consuming simulations and linking the pre-calculated results to obtain the auralized binaural sound at runtime.

Interfaces between the simulation modules have been defined and the simulation modules and their sophisticated background have been presented in detail. As the inside of the modules has been already under extensive research in the last years, the linking of the knowledge of these disciples yields this new auralization concept.

Furthermore, the machine’s signal and transfer characteristics are simulated for different, discrete working points and interpolation enables to auralize under various conditions inside a given range. A psychoacoustic approach, in terms of detection threshold and masking, leads to perception based quality of the final auralization result and effectively used simulation time.

The next step is the consequent implementation of this concept and the integration into the existing auralization software. First psychoacoustic listening test are to be performed to show the potential of the concept.

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