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Simulated Transfer Functions for the Auralization of Electrical Machines

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ABSTRACT

In the design process of electrical machines, the manufacturer would like to apply simulation methods based on CAD models in order to reduce the cost for prototypes. An important design parameter is the sound radiated from the vibrating surface of the complete machine including the housing components. In order to correctly assess the acoustic behavior of the machine, auralization including a realistic room acoustic simulation can be used. The machine can be virtually placed inside the actual environment it will later be employed in.

This paper presents methods to simulate the required transfer functions and prepare the data for real-time auralization in arbitrary room acoustic environments. Based on independent input data from numerical simulations that include the electromagnetic force excitation and the structural-dynamic behavior of the machine the sound radiation will be derived by means of Boundary-Element-Method (BEM) simulations. The presented approach makes use of the fact that all simulation steps are independent and can thus be calculated in parallel, reducing the computation time. The combination of the structural and the acoustic domain is then a simple vector multiplication, making it easy to include several load cases and operating conditions for the machine.

From the given data, two important acoustical parameters that are required for auralization – the radiated sound power and directivity – are calculated. Meshing, simulation and post-processing steps will be presented that produce data for the subsequent room acoustic simulation and auralization within reasonable time.

1. INTRODUCTION

Noise that is generated by electrical machines depends on several parameters, including the geometrical specifications and the operating conditions [1]. While measuring the radiated sound for varying different loads and driving current signals is at least tedious yet still possible, assessing the behavior for changes in the geometry of the stator and/or rotor is hardly feasible as it involves the construction of many prototypes. The manufacturers of electrical machines would thus like to simulate the acoustical behavior of their products before they are built.

The goal of such a simulation is a set of transfer functions for a specific operating condition and geometry, which relates the electric input signal to the acoustic output signal (Figure 1). Based on the electric current the force excitation is calculated by means of electromagnetic Finite-Element-Method (FEM). The propagation through the structure of the machine toward the surface is simulated by structural FEM and finally the sound radiation from the vibrating surface can be predicted by the acoustic Boundary-Element Method (BEM) [2]. Any change in the driving strategy or the design has to be reflected in the transfer vectors as quickly as possible, so that as many information as possible should be calculated offline and the independent computations should be performed in parallel.

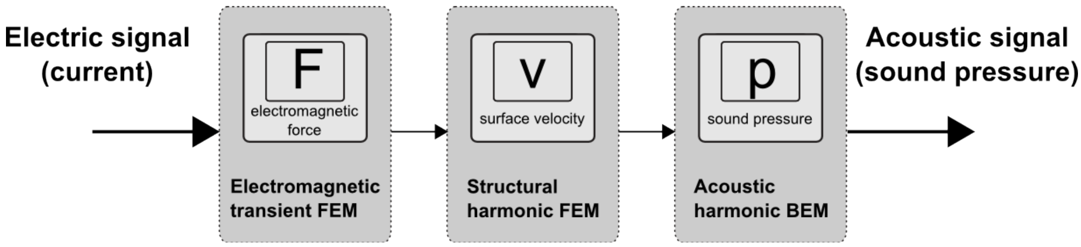

Figure 1 Simulation steps from the electric input signal to the acoustic output signal

In order to include the perception into the evaluation of the radiated noise and thus obtain a more realistic result, the noise signals can be auralized instead of relying only on a single-value parameter like sound pressure level or sound power [3]. Auralization also provides the possibility to virtually place one or several machines in a possible operating environment so that the complex sound field inside the room can be predicted with the help of the transfer vectors and a realistic room acoustic simulation [4].

As a practical example, the simulation steps in Figure 1 will be applied to a small induction machine (Figure 2). From the transfer vectors, two acoustical parameters that completely describe the source will be determined: the radiated sound power and the directivity function. Special focus will be laid on computation time and several ways to reduce it.

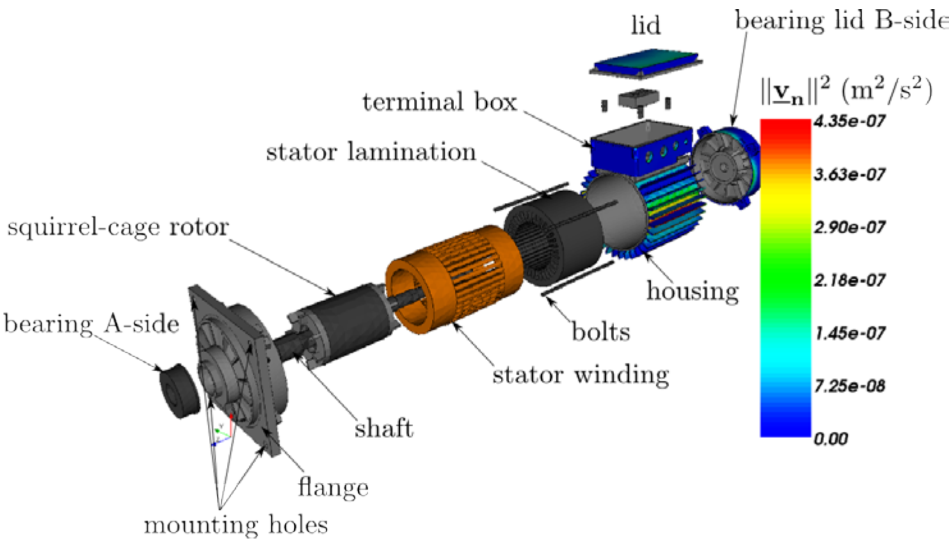

Figure 2 Mechanical model of the induction machine together with the normal surface velocity on the housing at 533 Hz

2. ELECTROMAGNETIC AND STRUCTURAL SIMULATION

The first steps in the simulation chain in Figure 1 reflect changes in the driving strategy and the stator/rotor configuration of the machine and are hence independent of the acoustical radiation.

The electromagnetic force excitation can be calculated based on the driving conditions. This is done using the software package *iMOOSE*, which is developed at the Institute of Electrical Machines in Aachen. Due to the cylindrical geometry of the stator the resulting force excitation occurs at distinct frequencies which make up the characteristic tonal nature of the noise that is emitted by electrical machines. The values of these frequencies are directly related to the rotation speed.

In order to determine how the force excitation is transmitted through the structure of the machine towards the exterior surface, Finite-Element-Method simulations can be performed based on a discretized structural mesh (Figure 3). This step is accomplished using the software *ANSYS*. The result is a set of transfer vectors between the force excitation at the stator and the surface velocity distribution on the housing of the machine.

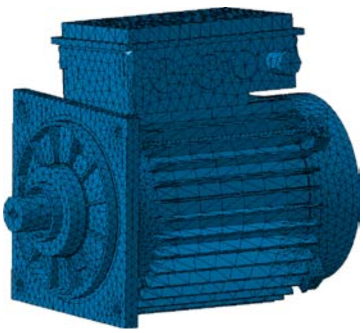

Figure 3 Structural mesh of the induction machine

3. ACOUSTIC BOUNDARY-ELEMENT-METHOD SIMULATION

The goal of the acoustical BEM simulations is to obtain the transfer vectors between the normal surface velocity on the machine and the far-field sound pressure at arbitrary locations in the free field. For all meshing and simulation steps the software *Virtual.Lab* by *LMS* is used.

Meshing

Since the memory requirements and the computational cost of the acoustic BEM rise with the square of the number of mesh nodes, the very detailed model that is used in the structural-dynamic analysis has to be converted into a mesh for the acoustic radiation that complies with the well-known six-elements-per-wavelength criterion. In this respect, it is often favorable to use several acoustic meshes in order to speed up the calculation time for lower frequencies where only a coarse discretization is required. The coarsening step from structural to acoustic mesh is performed in *LMS Virtual.Lab* with the *Skin Mesher* and *Wrapper Mesher* functionality.

For the presented induction machine, two acoustic meshes were created for a maximum simulation frequency of 2 kHz and 5 kHz, leading to average element edge lengths of roughly 28 mm and 10 mm, respectively (Figure 4). Figure 5 presents a plot of the maximum frequency quality criterion for the two acoustic meshes, showing that the coarser model can be used up to a maximum frequency of 2.8 kHz, whereas the more detailed model can be used up to 5.1 kHz. The meshes consist of 832 nodes and 4250 nodes, respectively, which means that the low-frequency model is smaller by a factor 5 and hence the memory requirement and the computation time are reduced by a factor 25. Compared to the structural mesh with about 210000 nodes the model size is reduced by a factor 50-250.

Figure 4 Acoustic meshes for different maximum simulation frequencies (left: 2 kHz, right: 5 kHz)

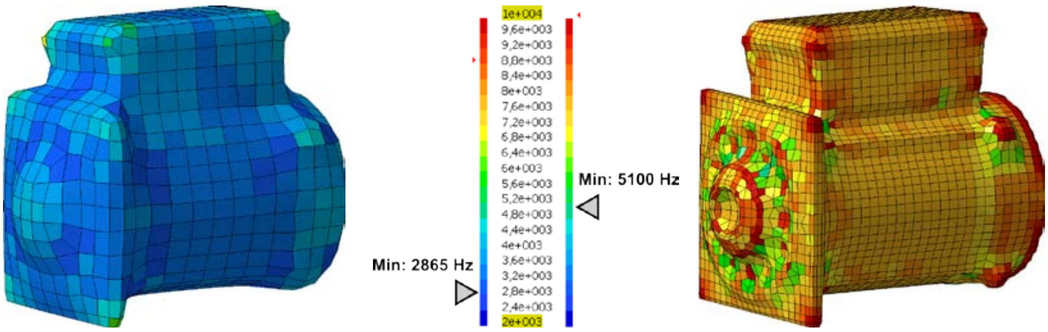

Figure 5 Plots of the maximum frequency quality criterion for the acoustic meshes

As the results for the surface velocity from the structural calculations are only available on the very fine mesh, a mapping of the data onto the acoustic mesh has to be performed. This is done using the mesh mapping function in *Virtual.Lab* which handles the connection between structural and acoustic nodes and applies a linear weighted sum in the case that multiple structural nodes affect the velocity at a single acoustic node.

Simulations

For each of the acoustic meshes the transfer vectors between the normal velocity at a single mesh node and the resulting pressure at a specified set of field points have to be determined. In *Virtual.Lab* this is implemented as the Acoustic Transfer Vector (ATV) set [5].

For each mesh node *i*, a unit normal velocity will be imposed while all other nodes have zero normal velocity and the BEM will be calculated with these boundary conditions. Determining the sound pressure at the field point *k* then only consists of a vector product of the surface velocity distribution ***v*** on the mesh and the transfer vectors:

(1)

This method is computationally very efficient, as the transfer vectors only have to be computed once for the same radiating surface, so that a recalculation for different operating conditions and stator/rotor setups is not necessary.

The computational cost of the ATV is connected both to the number of mesh nodes of the acoustic model as well as the number of field points. For the directivity and sound power calculations, spherical field point meshes are usually employed and care has to be taken that an adequate spatial sampling is chosen. Instead of the popular equiangular distribution, other field point meshes can provide the same spatial resolution with less sampling points. In this study, a hyperinterpolation grid was chosen that consists of 1/4th of the field points of an equiangular grid with the same sampling properties [6].

The resulting sound pressure *p* at the field points can finally be evaluated in terms of the total radiated sound power and the directivity. The sound power is defined as the surface integral over the normal component of the sound intensity vector :

(2)

where and are the density and speed of sound in air, respectively. Here, the plane wave approximation for the pressure in the far-field is used.

4. RESULTS

Figure 6 shows the influence of the number of mesh nodes and the number of fieldpoints on the computation time needed for the ATV at a single frequency. In the plot on the left, it becomes clear that the computation time rises with the square of the number of mesh nodes, affirming the approach to use meshes of different size for the corresponding frequency ranges.

In the figure on the right, the computation time is displayed in relation to the number of fieldpoints with the mesh size as the curve parameter. As can be expected for the BEM, the influence of the number of fieldpoints is only linear. Nonetheless, a reduction of the fieldpoints by a factor 0.25 leads to a reduction in computation time of roughly 50% per frequency bin.

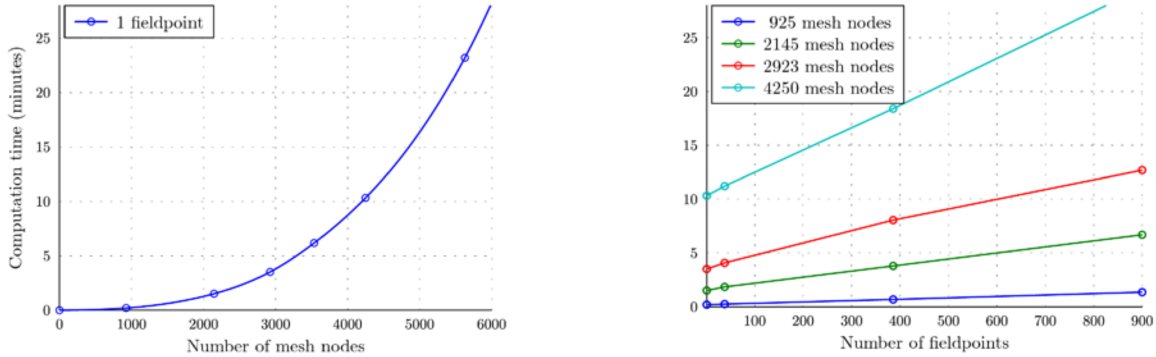

Figure 6 Influence of the number of mesh nodes and fieldpoints on the computation time

The result for the calculated sound power is presented in Figure 7. As already mentioned in Section 2, the radiated noise only contains some discrete frequencies. Figure 8 shows the directivities for three selected frequencies.

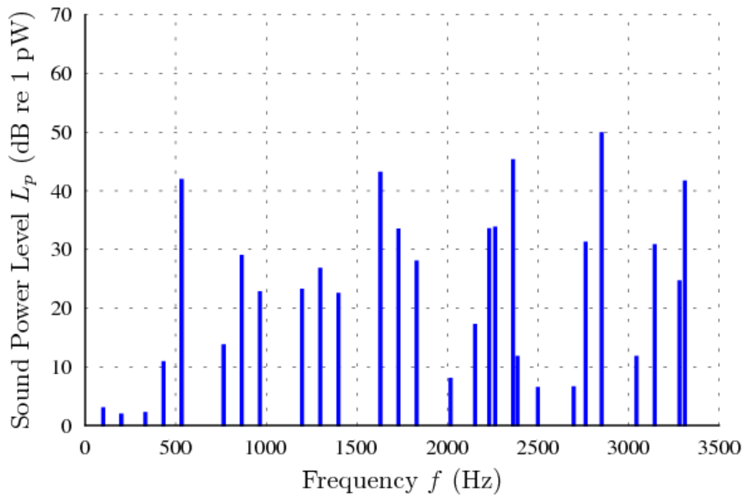

Figure 7 Simulated sound power level for the induction machine

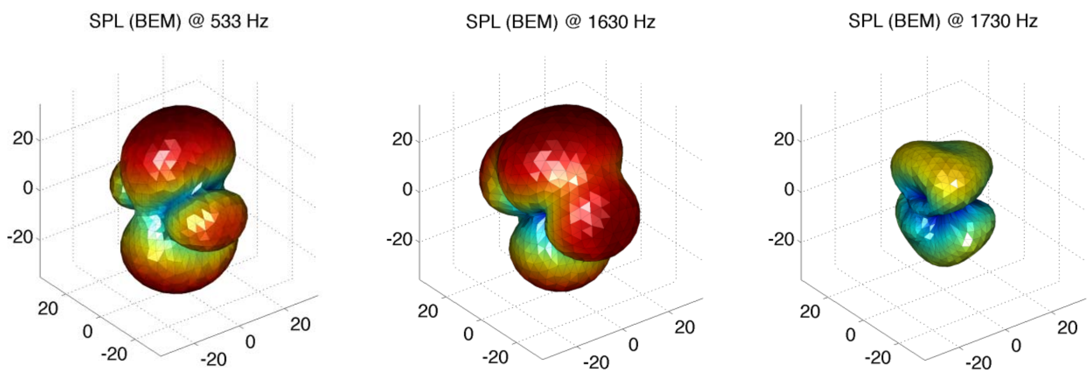

Figure 8 Radiation patterns for different frequencies

5. CONCLUSION AND OUTLOOK

Several ways to reduce the computation time during the simulation of transfer vectors for auralization have been presented and applied to a small induction machine. Advantage is taken of the fact that the calculations in different domains can be computed in parallel.

For the acoustic part, the BEM simulations are carried out for two acoustic meshes and a hyperinterpolation fieldpoint grid. In comparison to simulations with only a single acoustic mesh and using the equiangular fieldpoint mesh, about 74% of the computation time per frequency bin can be saved using the presented approach. A further speed-up could possibly be achieved using the Fast Multipole BEM (FMBEM) but for the moment, this method is only implemented for linear triangular elements, which are not supported by the wrapper mesher.

Possible future work can on one hand focus on the numerical simulations in the other domains, meaning the electromagnetic and structural FEM. The question is whether the very fine discretization of the geometry is necessary in order to obtain accurate results. If the models for the FEM simulations can be reduced additional computation time could be saved. At the moment, the time needed for the electromagnetic FEM is roughly 3 days for the frequency range up to 5 kHz and 1 Hz resolution. The structural modal analysis takes about 4 hours.

A different approach could focus on the audibility of differences between transfer vectors. For this problem, listening tests in a virtual acoustic environment would have to be carried out. The tests could be carried out for varying coarseness of the acoustic meshes leading to a threshold value from which a set of transfer vectors leads to a noticeably different listening experience.

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