NOISE PREDICTION FOR ELECTRIC MOTORS BY COUPLING ELECTROMAGNETIC AND VIBROACOUSTIC SIMULATION TOOLS

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ABSTRACT

1 INTRODUCTION – NOISE FROM ELECTRIC MOTORS

After decades of experience in fine-tuning the noise of internal combustion (IC) engines, a new challenge awaits the automotive industry : optimization of the powertrain sound in hybrid and electric vehicles. Although the overall noise level produced by an electric vehicle is significantly lower than for a classical IC-engined vehicle, electrical motor noise is marked by high-frequency components which can be perceived as annoying for both passengers and the environment. Therefore, the importance of predicting noise from electrical drives and motors has received renewed interest. This presentation will highlight how electromagnetic (EM) and vibroacoustic (VA) simulation tools can be coupled in order to predict and optimize the noise levels and frequency content of sound radiated by a typical electrical motor used in automotive drivetrains.

A major component is the noise caused by motor housing vibrations which are generated electro-mechanically, i.e. by the Lorentz forces induced by the magnetic forces acting upon the currents in the stator windings [1]. The LMS Virtual.Lab Acoustics, from Siemens PLM Software enables engineers to predict and optimize this noise up-front in the design phase. Although the total surface vibrations of the motor's housing are driven by the combination of mechanical bearing forces and electro-mechanical Lorentz forces, only the process of obtaining EM-induced noise is highlighted here. The paper will elucidate the process of predicting electromagnetically induced forces in the time domain, mapping these EM forces onto a vibroacoustic simulation model in the frequency domain and obtaining radiated sound power for a typical three-phase permanent magnet synchronous motor.

2 COMPUTING AND MAPPING EM FORCES ON THE STATOR

2.1 Computing EM forces with JMAG

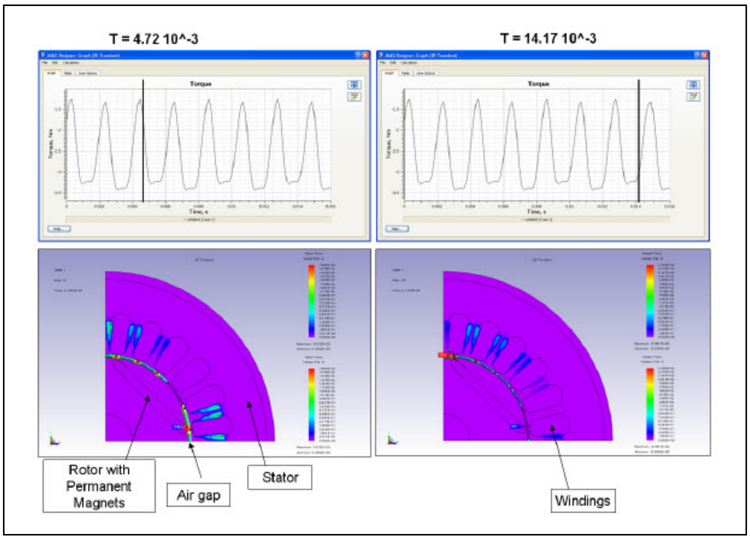

Fig. 1 : EM Simulation in JMAG – Nodal force distribution on the stator

First, an electromechanical computation was carried out for a three-phase permanent magnet synchronous motor with four poles using the ElectroMagnetic Simulation software package JMAG, developed and marketed by JSOL. As can be seen in Fig. 1, the software allows the definition of only a part of the of the axisymmetric EM problem to obtain the motor characteristics – e.g. torque (RPM), power (RPM) – for the complete electric motor. In this case, only a quarter-model was necessary, as we are dealing with a four-pole motor. Figure 1 plots the EM-induced Lorentz forces in the stator core as a function of time. It is clear that the largest EM forces are being generated near to the stator-air interface, and also across the air gap between stator and rotor.

2.2 Mapping EM forces to structural FEM – Influence of mapping depth

Once the forces on the EM stator mesh have been obtained, they can be mapped onto a 3D structural FEM mesh for dynamic analysis using a conservative mapping algorithm. JMAG automatically completes the extension of the force results from the 90 degrees quarter-model to the remaining 270 degrees for the axisymmetric stator geometry. The forces, which are expressed in N/m for the 2D "slice", are also extruded into the axial direction to obtain full 3D forces at each node on the structural FEM mesh. Next to the geometrical mapping, the forces are also transformed from the time domain to the frequency domain using Fast Fourier Transform algorithms, including windowing functions.

Figure 1 already showed that EM force density is the highest near the stator-air interface. Hence, the question can be asked how "deep" these forces have to be mapped into the stator iron volume, and how much of the stator surface needs to be included. For this purpose, 4 different regions of the stator mesh have been used to map the forces, each one corresponding to a different mapping depth. The 4 “mapping depth” configurations are illustrated in Figure 2, where “larger stator surface” indicates the stator surface facing the winding slots.

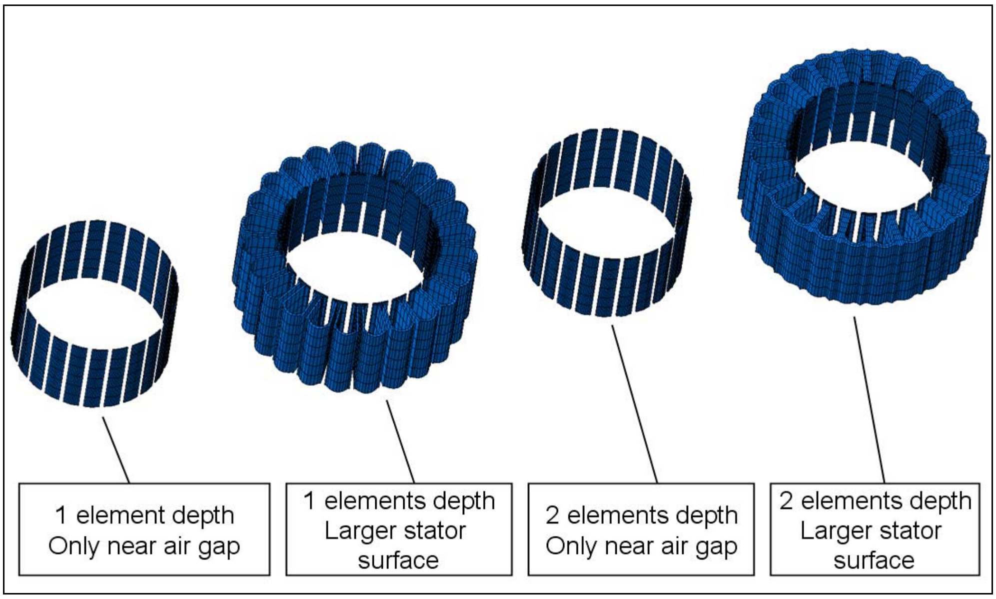

Fig. 2 : Four different stator regions corresponding to different mapping depths

Moreover, we have to deal with some uncertainty with respect to the structural properties of the stator core, which in practice consists of many steel lamellas isolated by layers of varnish. In our case, the stator core has been simplified to a single property card for the dynamic analysis, with a property stiffness matrix taking into account the orthotropic character of the stator core.

3 VIBRO-ACOUSTIC ANALYSIS OF STATOR-HOUSING ASSEMBLY

3.1 Structural vibration analysis with modal representation

To compute the structural vibrations caused by the EM forces, a structural modal representation of the stator and housing was selected. Figure 3 shows the first flexible modes of the stator-windings-housing assembly (one of the end caps was left out of the picture for clarity).

The combination of the frequency domain EM force loads and structural modes yields frequency-dependent vibration patterns, which are then ported onto an Acoustic FEM model as excitation in the form of normal velocity boundary conditions.

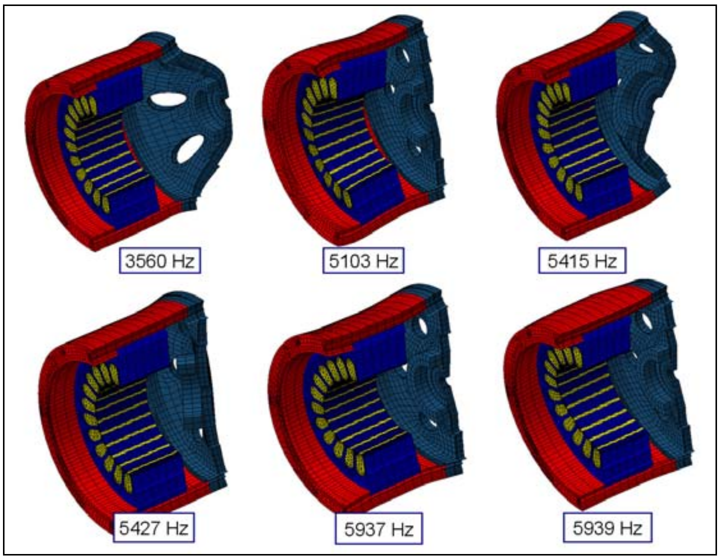

Fig. 3 : Structural modes of stator-windings-housing assembly

3.2 Acoustic FEM analysis using PML/AML methodology

The acoustic radiation is obtained by means of an Acoustic FEM model, modeling the air volume around the vibrating stator and housing assembly. The Sommerfeld radiation condition – sound waves should propagate to infinity without being reflected – is realized by the PML (Perfectly Matched Layer) methodology [2,3], which consists in applying a special layer of elements to the boundary of the conventional FEM mesh, which ensures that no waves are reflected from this boundary.

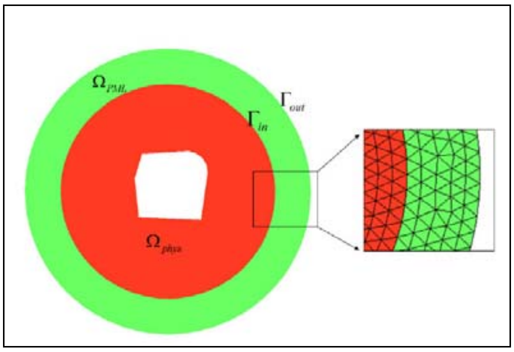

Fig. 4 : Conventional FEM mesh (red) and PML absorption layer (green)

This is realized by an absorption function *f(x)* which increases from 0 at the inner PML boundary Γ_{in} to a finite value at the outer PML boundary Γ_{out}. The sound wave propagates further in the domain Ω_{PML}, but is being progressively damped by the absorption function. The damping of the PML medium is not isotropic however, because the absorption function is defined along a „locally conformal“ vector direction n with respect to the boundary Γ_{in} In practice, the PML layer does not have to be modeled explicitly by the AML (Automatic-Extrusion Matched Layer) technique: the PML condition is directly applied to the FEM boundary , and the PML mesh is extruded mathematically from this boundary.

Finally, the acoustic pressure in microphone positions in the free field beyond the PML/AML boundary is obtained directly from the pressure and particle velocity on this boundary by evaluation of the Kirchhoff-Helmholtz surface integral, where *G(x,y)* is the Green kernel function, and *p(y)* and *dp(y)/dn* are sound pressure and sound pressure gradient on the boundary Γ_{in}

$$p(x) = \int_{\Gamma_{in}} G(x,y)\frac{\partial p(y)}{\partial n} + p(y)\frac{\partial G(x,y)}{\partial n}\, d\Gamma_{in}$$

4 ACOUSTIC ANALYSIS RESULTS – SOUND POWER

Figure 5 shows the Acoustic FEM model of the stator-housing assembly for sound radiation analysis :

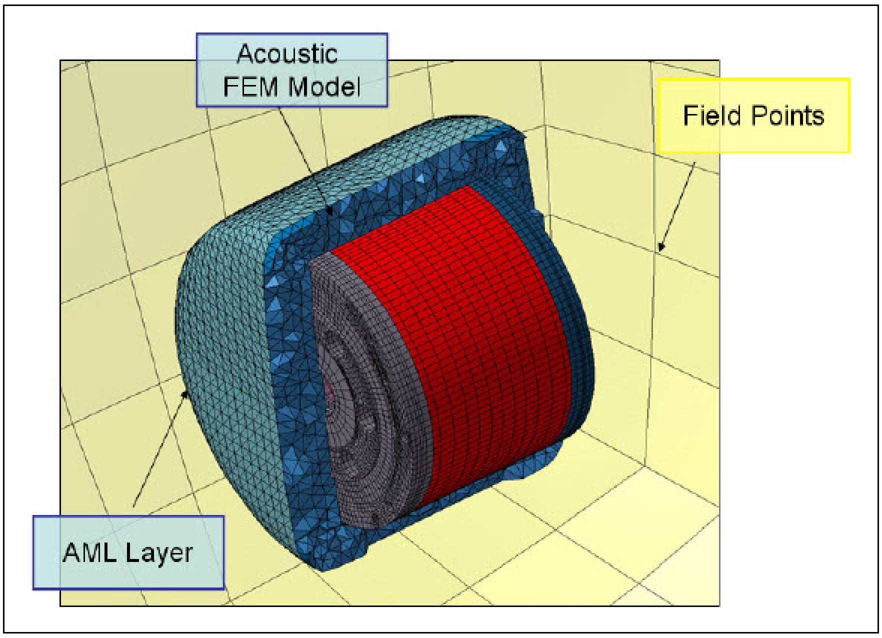

Fig. 5 : Acoustic FEM PML/AML model set-up (acoustic mesh around electric motor in blue)

The sound power radiated by the electric motor has been computed over a frequency range from 20 Hz to 4000 Hz using a powerful iterative Krylov solver technique, for each of the four „stator mapping depth“ configurations. The resulting sound power curves are plotted below in Figure 6, with frequency on the X-axis and Sound Power in dB on the Y-axis.

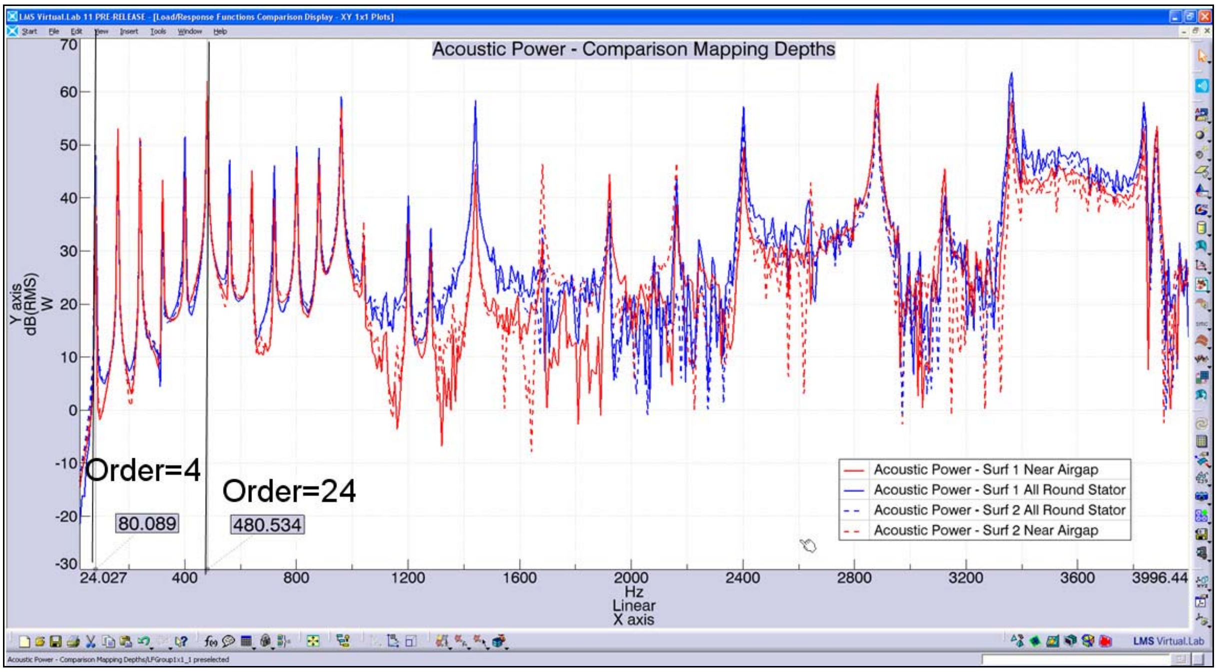

Fig. 6 : Sound power results [20 Hz – 4000 Hz] for 4 different stator mapping depths

These curves show that mapping depth does not affect the sound power results in the lower frequency range (up to 1 kHz), but significant differences occur at higher frequencies. The difference between mapping 1 or 2 elements deep is relatively small, but differences in sound power of 5 dB to 10 dB are observed when comparing the „air gap only“ results (in red) to the „air gap plus larger stator surface“ results (in blue) , see Fig. 2 for the configurations. Also, the response is dominated by 4th-order and 24th-order harmonics, consistent with a 4-pole machine containing 24 stator slots at 1200 RPM.

5 CONCLUSIONS

This paper discusses a process to map forces from an electro-magnetic simulation package (JMAG) to a vibro-acoustic simulation tool (LMS Virtual.Lab Acoustics) - using a 3-phase permanent magnet synchronous motor as a case study. For different mapping depths , time domain forces were obtained and transformed to the frequency domain to compute the vibration of the stator-windings-housing assembly using modal representation. Through a highly performant modeling (PML/AML)and solving technology (iterative Krylov solver) available in Virtual.Lab Acoustic FEM, the radiated sound power was computed in the 20 – 4000 Hz frequency range. Results show that the amount of stator-air interface surface used in the force mapping

– in particular adding the surface facing the stator winding slots - can have a considerable influence on the sound power results (5-10 dB difference).

Once a good mapping process has been established, several optimization studies can be executed. Some of these aim at tackling the noise problem at the structural transfer level (dynamics of the stator-housing assembly) while others work closer to the source, trying to minimize the currents responsible for the large forces at the stator surface near the air gap, which are responsible for the EM-induced forces. The latter optimization loop, minizing current while keeping torque output as high as possible, was carried out with Virtual.Lab Acoustics in [4] for a switched reluctance motor.

6 REFERENCES

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