

Simulation of the Noise Radiated by an Automotive Electric Motor: Influence of the Motor Defects

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ABSTRACT

The noise radiated by an electrical motor is very different from the one generated by an internal combustion engine. It is characterized by the emergence of high frequency pure tones that can be annoying and badly perceived by future drivers, even if the overall noise level is lower than that of a combustion engine.

A simulation methodology has been proposed, consisting in a multi-physical approach to simulate the dynamic forces and noise radiated by electric motors. The principle is first to calculate the excitation due to electromagnetic phenomena (Maxwell forces) using an electromagnetic finite element solver. This excitation is then projected onto the structure mesh of the stator in order to calculate the dynamic response. Finally, the radiated sound power is calculated with the aid of a standard acoustic finite element method. The calculation methodology assumes a weak coupling between the different physical levels. It has been validated by comparison with the experiment.

This simulation only considers the excitation generated by a perfect machine. This paper focuses on the possibility to include in this simulation the defects related to a real machine such as static eccentricity, dynamic eccentricity or short-circuit in order to enhance its accuracy. The excitations are analyzed in terms of excitation content (frequency content and spatial distribution) and the consequences on the sound power radiated by the machine are discussed.

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INTRODUCTION

The automotive industry has entered a phase of change due to environmental considerations. Hybrid and electric vehicles have emerged. The vibroacoustic behavior (knowledge of the source mechanisms and expertise regarding the integration of this source of noise and vibration inside the vehicle structure) of combustion engines is now well controlled. This knowledge cannot be directly transferred to these new vehicles, either hybrid or electric. Therefore, it is necessary to build a new expertise and new tools in order to understand and optimize electric motors and their integration. This paper takes part in this process: the goal is to predict the vibroacoustic characteristics of a motor during the design phase.

Noise and vibrations generated by an electric motor can be divided into three main contributions related to three distinct sources [1]: mechanical, aerodynamical and electromagnetic. Mechanical noise and vibrations are related to the assembly. The friction and banging noise may be due to bearings, gears, possibly to the friction of the brushes on the rotor. These sources are highly dependent to the rotational speed.

In order to cool the motor, a fan is often mounted at the shaft end. Its goal is to gather the air up and force it to flow through the air gap. Just as any fan, it radiates noise. It is commonly accepted [2] that the acoustic power radiated by an axial fan is proportional to the power 5 of the rotational speed. Finally, note that the salient rotor poles may be the cause of an aerodynamic noise contribution. The levels of aerodynamic and mechanical noise are the highest at high speed.

Electromagnetic noise and vibrations are due to electromagnetic excitations that occur at the air gap of the motor. These are mainly radial dynamic excitations which is useless for the motor operation. The tangential dynamic contributions that create torque are usually lower. Many parameters influence the content of the excitation [3] such as the motor topology (number of slots and poles), the pole shape, the slot shape or the motor drive (currents shape). The amplitude of these excitations is not necessarily proportional to the rotational speed. Thus, the electromagnetic noise can be predominant at low speed.

A methodology has been developed in order to estimate the noise radiated by the machine due to electromagnetic phenomena. This requires the estimation of the forces applied to the stator, to calculate the dynamic response of the stator, and then deduce the radiated noise. Electromagnetic, mechanical and acoustic phenomena must be taken into account. This is a multiphysical problem for which it is necessary to combine elements of electromagnetic finite element calculations, dynamic finite element calculations and acoustic finite element calculations. This is the key point of this approach. This type of calculation has been presented and implemented by several authors. Neves et al. [4], [5] applied it to a switched reluctance motor (SRM) by using simplifying assumptions. They showed the relevance of the approach. Furlan et al. [6] used this methodology to calculate the noise radiated by a DC electric motor. Schlensok et al. [7] applied it to an induction machine with a squirrel-cage rotor. Rainer et al. [8] computed the dynamic response of a skewed induction machine and studied the accuracy in the frequency domain. Pellerey et al. [3] also applied this methodology to a wound-rotor synchronous motor.

The implementation of the simulation method has already been detailed [9], but this paper focuses specifically on the integration of the motor's defaults into the simulation methodology and its consequences on the calculated radiated noise. Typical simulation methods involve electrical machines that are supposed perfect. This results in a low number of excitation contributions from of the electromagnetic simulation [9]. In practice, electrical machines have defects, which generate new excitations (compared to the perfect case) and thus new contributions that can be observed in the spectrum of radiated sound power.

The main defects to be considered in this paper are:

- Short-circuit between coil turns,
- Static eccentricity,
- Dynamic eccentricity.

PRESENTATION OF THE SIMULATION METHODOLOGY

The basic principle of the calculation is to perform a weakly-coupled electromagnetic-dynamic calculation. The electric motor is modeled using a finite element electromagnetic software program in order to calculate the electromagnetic excitations applied to the stator.

This excitation data is projected onto the structural mesh of the e-machine with the aid of a dedicated mapping tool and a dynamic calculation can be performed using a finite element method. As this kind of procedure is included in an acoustic scope, the output value of interest is the vibration velocity of the stator. The last step is the calculation of the vibrating structure's radiation. An acoustic finite element method (FEM) is used (a boundary element method (BEM) can also be used).

Vibration velocity is taken into account as a boundary condition. The output data is the sound power radiated by the machine. Since this is a typical calculation, this step is not detailed in this paper.

Figure 1 gives a scheme of the 3-step multiphysical calculation procedure.

Electromagnetic Excitation

As stated in [9], Maxwell pressure is taken as the main phenomenon responsible for the stator vibration and the stator radiation. Flux density and thus Maxwell pressure can be calculated using finite element electromagnetic solvers. Depending on whether the electrical machine is skewed, one or several slices of the machine are modeled to evaluate the electromagnetic forces. If the rotor is not skewed, the magnetic excitations (the radial component as well as the tangential component) are considered constant through the length of the magnetic circuit. If it is, a linear evolution of the magnetic excitations over the machine's length is assumed.

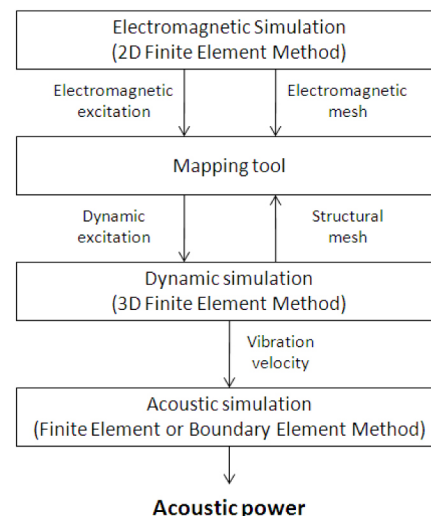


Figure 1. Basic principle of the calculation procedure.

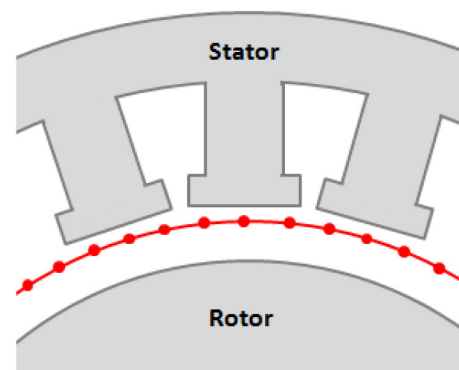


Figure 2. Calculation points of the Maxwell pressure inside the air gap.

The Maxwell pressure is calculated for virtual sensors located inside the air gap [3, 9] (Figure 2), close to the stator (at 75% of the air gap). Since the rotor is moving, the electromagnetic solver is based on a time resolution so that the electromagnetic

calculation results in a time evolution of the magnetic excitation at each virtual sensor. Thus, for each motor speed, the electromagnetic simulation provides two time-space excitation matrices (one related to the radial component, the second related to the tangential component). The influence of every relevant parameter is contained in this simulation: number of poles, number of stator slots, number of rotor slots, current shape, eccentricity and saturation of the magnetic core. These parameters affect the excitation content in the time domain as well as its spatial distribution.

Projection of Electromagnetic Excitations

The first step is to transform the time excitations into a sum of frequency excitations with the aid of Fourier series. Then, the Maxwell pressure (expressed in N/m^2) has to be projected onto the structural mesh and transformed into forces (in N). For each interface node (Interface nodes are the nodes located close to the air gap, where an excitation is applied) of the structural mesh, the corresponding surface force density is multiplied by the area of the surface located around the node (this value is calculated and depends on the topology of the mesh structure). Thus, two excitation spectra (radial and tangential) are calculated independently for each interface node of the structural mesh. Excitation data are exported in format that can be read by the structural FEM solver and can be applied to the stator finite element model in order to perform dynamic calculations in the frequency domain. This mapping algorithm can be applied to any type of structural mesh.

Dynamic Simulations

The dynamic calculation is based on the modal frequency response. In a first step, the modal basis of the structure is calculated. By knowing the applied loads, it is used in order to estimate the structural response of the stator. [Figure 3](#) illustrates the calculation process.

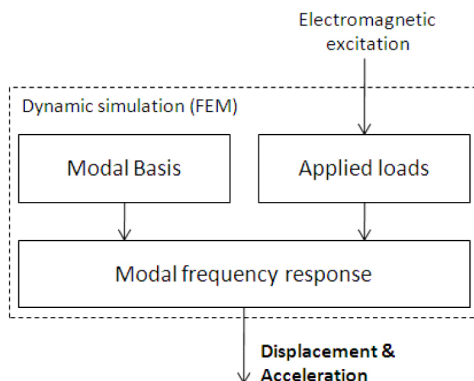


Figure 3. Principle of the dynamic simulation.

As it is a quite typical operation, the calculation of the sound radiation is not discussed in this paper. It is based on a finite element or boundary element method where the vibration velocity field at the outer skin of the machine is taken as a boundary condition. This time consuming step can even be skipped with a rough estimate of the radiation efficiency of the structure. The sound power radiated by the machine is directly deducted from the vibration results without any acoustic calculation.

MODELING OF THE ELECTRIC MOTOR

The methodology presented in this paper is applied to a permanent magnet synchronous motor. Its characteristics are given in [table 1](#). This is a generic basic machine as it aims at highlighting the main phenomena.

Table 1. Characteristics of the studied motor.

Power	50kW
Number of phases	3
Number of pole pairs	2
Number of stator slots	48
Number of coil turns per phase	192
Air gap	0.84mm
Speed	1 000rpm – 10 000rpm
Max current	132 A

Both an electromagnetic and a dynamic finite element model have been built in order to apply the proposed simulation methodology.

Electromagnetic Model

Based on the cross-section of the machine, a 2D electromagnetic model of the machine is built. Due to symmetry considerations, only a quarter of the motor can be modeled. It is illustrated on [figure 4](#) (the whole motor is displayed). It is made of about 12 000 nodes and 6 000 elements. A sinusoidal current is imposed inside the coils. [Figure 5](#) gives a detailed view of the electromagnetic model.

With the aid of Cedrat *Flux2D* software, electromagnetic transient simulations are performed for speed values from 1 000 rpm to 10 000 rpm (step: 1 000 rpm), resulting in flux density maps as illustrated on [figure 6](#) and excitation data illustrated on [figure 7](#) (excitation map: radial excitation as functions of the spatial position on the stator and of the rotor position).

These data are exported in order to be projected onto the structural model of the machine.

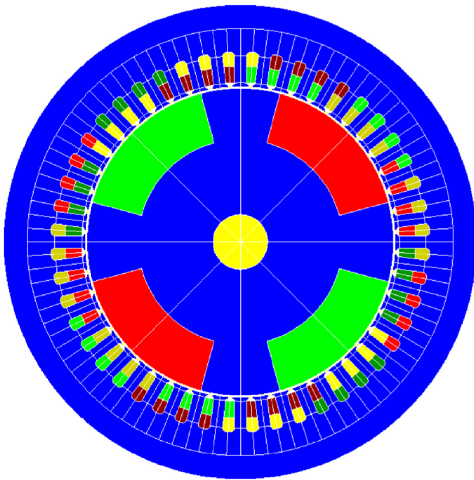


Figure 4. Illustration of the electromagnetic model.

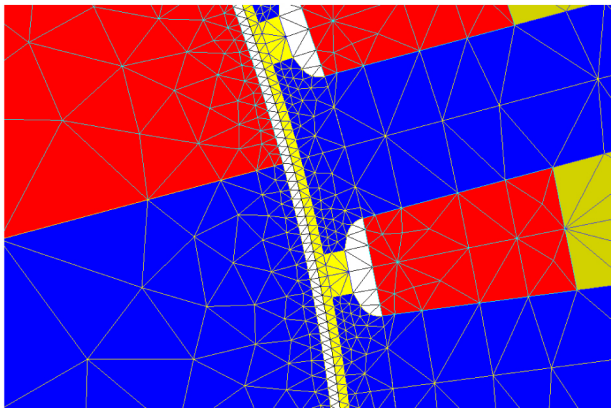


Figure 5. Detail of the electromagnetic model.

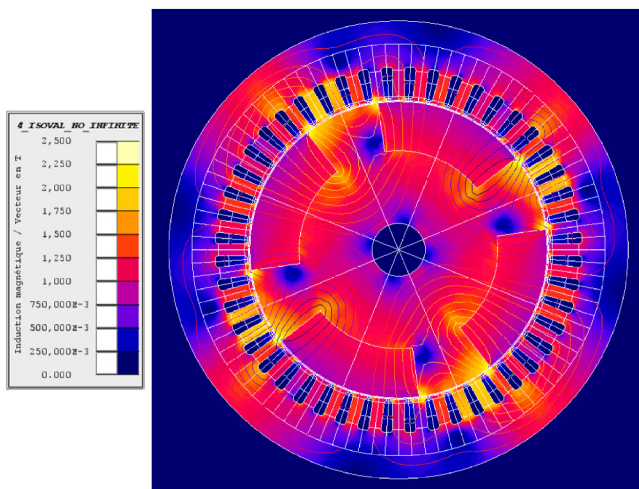


Figure 6. Example of a flux density map (including field lines) obtained for a given rotor position

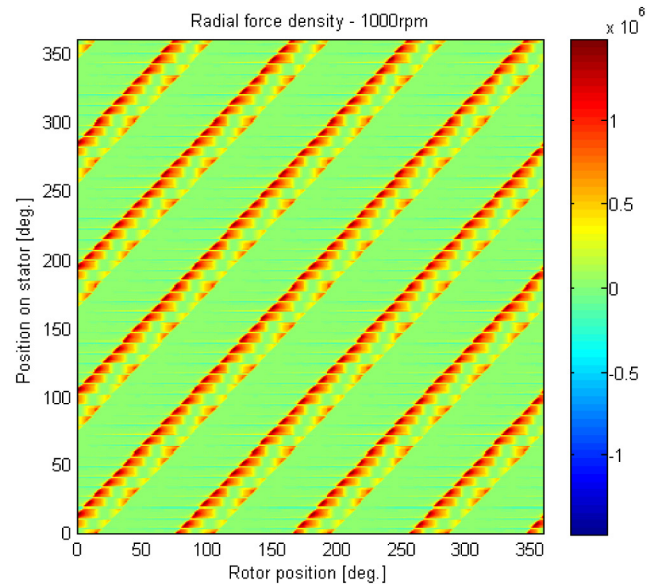


Figure 7. Radial contribution of the air gap Maxwell pressure (in Pa) as functions of the position on the stator (space) and of the rotor position (time).

Dynamic Model

Based on the cross section of the e-machine, a simplified geometry is generated. It is shown on [figure 8](#).

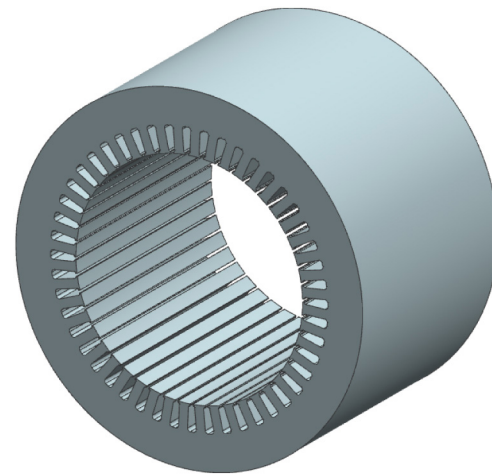


Figure 8. Simplified geometry based on the machine's cross section.

The finite element model of the electric motor is mainly made of solid elements. As illustrated on [figure 9](#), it consists of two main parts:

- The magnetic core is the active magnetic part of the stator. It is made of laminated magnetic steel. As it is not possible to generate a detailed mesh of the steel layers, a homogeneous equivalent material is used. Its characteristics are determined either through a model updating process [10], or through a calculation procedure based on the properties of materials of which the stack is made. The mass of the windings is distributed onto the slot surface.