

Electromagnetic and Structural Coupled Simulation to Investigate NVH Behavior of an Electrical Automotive Powertrain

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ABSTRACT

RENAULT aims to become the first full-line manufacturer putting to market zero-emission affordable electrical vehicles and is therefore developing 100 % electric powertrains. NVH problems related to electric machine design have nothing in common with those of gasoline or diesel engines: electric whistling is a high frequency harmonic phenomenon, easily detectable due to the low background noise of a non-thermal vehicle and mainly perceived as very unpleasant by the customer.

Therefore we have developed a coupled numerical simulation between electromagnetic and structural models, making it possible to understand the influence of magnetic parts design on noise and vibration level. Impact of the spatial and time coherence between magnetic pressures and vibration modes of the motor will be explained. The novelty of our approach is to already take into account the whole powertrain structure radiation, including reducer and power supply boxes. Moreover we investigate the influence of the harmonic content of the supply current due to the regulation system, as well as the tangential forces effect on stator teeth.

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INTRODUCTION

Automotive is facing a major transformation with emergence of hybrid and electrical vehicles. Most people expect a new generation of silent vehicle and appreciate the low background noise level of the non-thermal drive. Remaining electrical whistling and gear whining noise are therefore all the more perceived as unpleasant that they are harmonic, high frequency and very emerging. It is thus necessary to build a new expertise on electric machine design and new tools to investigate in detail magnetic noises.

Many papers deal with magnetic noise simulation or electric machine optimization. Most authors consider that the acoustic level is mainly produced by stator ovalisation and breathing modes under radial Maxwell pressure ([1], [2] and [3]). Our paper gives an overview of the studies performed by RENAULT and Electromagnetic Laboratory of Compiègne ([4], [5], [6], and [7]). All automotive manufacturers have developed their own numerical approaches - based on 3D

Finite Element model - to foresee vibratory behavior of internal combustion engine. A similar approach has been set up by RENAULT to develop electrical powertrains.

In a first part, we describe the coupling between a 2D electromagnetic model and 3D structural finite element model. This approach is considered as the best compromise between computation times and model management difficulties. We disregard set-up theoretical grounds, already issued in many papers ([1], [2], [3]), but focus on main operational difficulties emerging in an industrial context. Among them, we find the management of various kinds of model with respect to computation time, data size and accuracy.

The novelty of our approach lies in taking into account tangential forces on stator teeth and realistic supply harmonics. Furthermore we show that the simulation cannot be restricted to the stator housing, but also to the whole powertrain including the rotor and the reducer shafts. Due to

its high frequency, the PWM noise is not covered in this paper.

All results were obtained on a 70 kW Wound Rotor Synchronous Machine (figure 1). The simulation and measurement were performed for a run up. Vibration level due to magnetic forces is given as an acceleration level on the magnetic noise reference point, a point on the middle stator section, in a cylindrical reference system (figure 1).

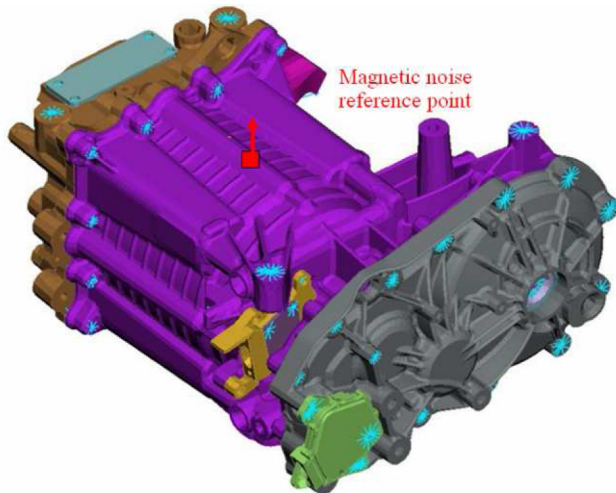


Figure 1. Model of the electrical machine and reducer.

BODY

I. COUPLED SIMULATION TOOLS SET-UP

The approach that has been implemented by RENAULT consists in coupling the electromagnetic model - used for the design of electromagnetic parts - and the NVH finite element model. The management of magnetic rotating excitations as well as the specific harmonic behavior of electric machines require the development of bridges to connect various softwares. However, the approach remains similar as for ICE. Our choice was not to develop a completely new optimal simulation chain but to connect the simulation tools and numerical model used everyday by the engineers in charge of magnetic and NVH design. This way our simulation chain is shared by all development departments and does not require any additional work to build specific models.

For non-skewed machine, this coupling of 2D electromagnetic model with the 3D structural finite element model seems to be the best compromise between accuracy, computation time and model management. This complete simulation chain allows us to:

- Investigate the electromagnetic behavior of the machine, especially the coupling between supply currents and the magnetic design [4][6]
- Foresee the coupling of magnetic forces in the air gap with modal behavior of the powertrain.

- Reduce vibration level thanks to an optimization of magnetic parts.
- Assess the influence of manufacturing tolerances, such as rotor eccentricity [5].

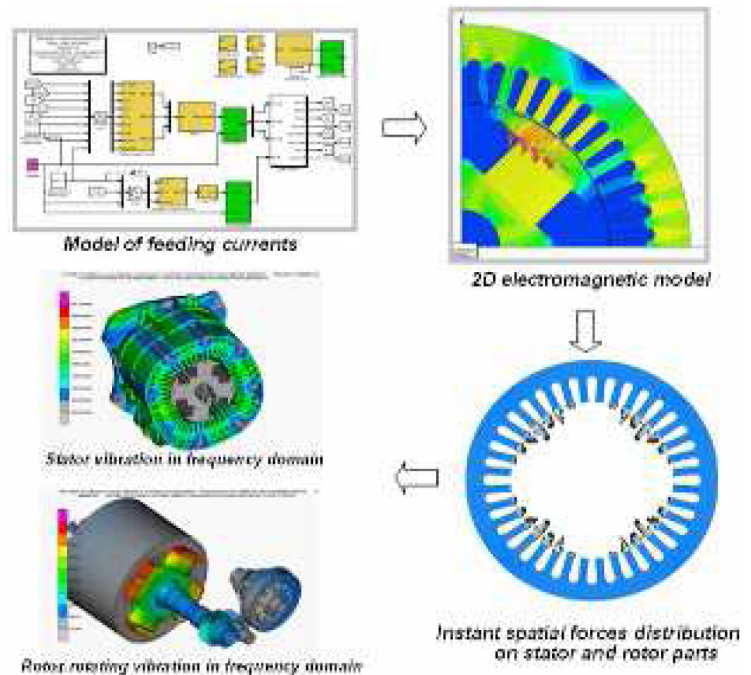


Figure 2. Principle of the coupled electromagnetic & NVH simulation

Magnetic simulation

Engineers in charge of the magnetic parts design commonly use a two dimensional symmetric model for the magnetic simulation, MAXWELL 2D model by RENAULT. In their everyday work, they rarely consider the pressure distribution in the air gap, but focus mainly on electrical parameters or local magnetic saturation phenomenon.

The first stage consists in the post processing of the 2D magnetic simulation to obtain the Maxwell magnetic pressure in the air gap. The method is well described by J. Le Besnerais [1] or P. Pellerey [4]. The radial and tangential Maxwell pressure (σ_r , σ_t) are given by following relationship to magnetic induction and permeability.

$$\sigma_r = \frac{B_r^2 - B_t^2}{2\mu_0} \quad \sigma_t = \frac{B_r B_t}{\mu_0}$$

Hypothesis and practical details can be found in [1] [2] and [4]. Otherwise, all magnetic simulation softwares allow exporting these data with more or less difficulties. From this stage we retrieve radial and tangential Maxwell pressures on stator teeth and rotor poles.

Most publications only consider the radial behavior of the stator. The novelty of our approach is to take into account both tangential forces on the teeth and rotating vibration of

the rotor. We will see further that these forces cannot be neglected, especially when investigating the behavior of the whole powertrain. Tangential forces on the stator and on the rotor do not contribute to the machine acoustic radiation but generally excite the reducer housing and all auxiliaries with mechanical connections to the machine.

Numerical considerations

The coupling of electric, magnetic or NVH models requires the development of software bridges between softwares with various input and output file formats, files size, time or space description accuracy. This section will present a quick overview of main difficulties. Most practical details have already been covered by P. Pellerey in [4].

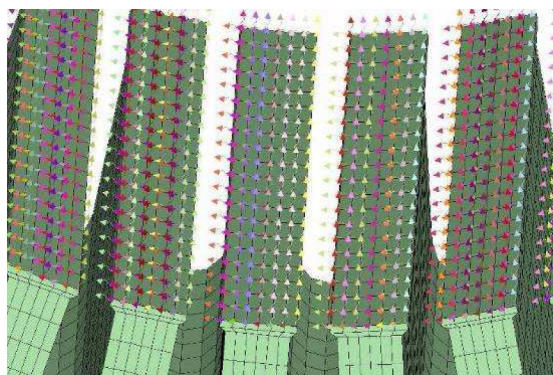


Figure 3a. Stator teeth structural mesh

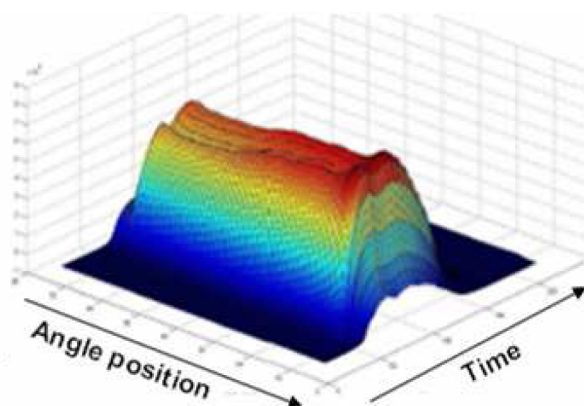


Figure 3b. Maxwell pressure on a tooth

The electromagnetic 2D model is based on a very fine meshing size, about 0,1 mm on the air gap limit, in comparison with the structural meshing size, between 3 and 5mm. Even if this projection induces an accuracy loss of the Maxwell pressure spatial description, the resulting forces distribution is sufficient for NVH purpose. In fact, the first spatial strong harmonic of this forces distribution corresponds to the stator teeth number, 48 in present case. Details of the pressure field on a tooth will appear as a multiple of this fundamental stator harmonic. Even if a coarse meshing of the stator teeth will slightly affect the resulting force on every

tooth, the harmonic content of the vibration level will not be modified.

The main operational difficulty remains the smart management of the amount of data and computation duration. The magnetic simulation is done in the time domain with a sharp description of the air gap. It results in huge files, giving data for each rotor angle position. Moreover the NVH structural analysis requires a full run up of the machine with quite small speed steps, every 100 rpm in our case, to make sure we do not miss any critical structural vibration mode.

To overcome file size and computation time difficulties, the magnetic simulation is only launched for about ten rotation speeds. For all rotor positions of a given speed, the Maxwell pressure distribution is projected on the structural meshing and then converted into the frequency domain using a Fourier transformation. Resulting files contain Maxwell forces on each nodes of the structural model for a list of frequencies. These frequencies are harmonic multiples of rotation speed. As most of them exceed the frequency range considered for NVH analysis, the file can be truncated.

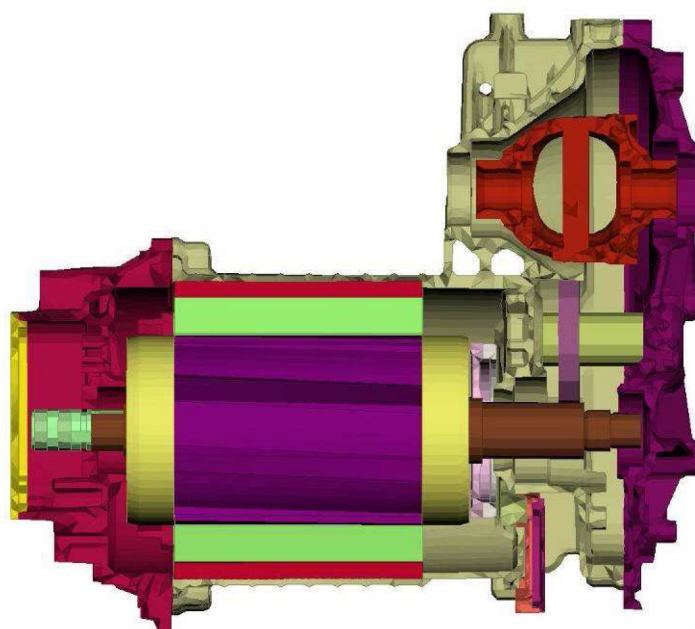


Figure 4. Model of an electrical machine with reducer (including shafts)

These excitation files for a few rotation speeds are then interpolated for each speed of the structural simulation, every 100 rpm in our case. This interpolation is completed following each harmonic. It is built on the hypothesis that excitation evolution versus speed is quite monotonous. Therefore it means a consideration of the current regulation strategy for the selection of the magnetic simulation speed cases [7].

The structural model used for NVH is based on a three dimensional accurate meshing of all components of the powertrain. Its size is about 300 000 elements and 500 000