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# Experimental Validation of a Mesh-to-Mesh Magnetic Force Projection for e-NVH Simulation

Raphaël Pile<sup>1</sup>, Jean Le Besnerais<sup>2</sup>, Martin Glesser<sup>2</sup>, Guillaume Parent<sup>1</sup>, and Yvonnick Le Menach<sup>3</sup>

<sup>1</sup>Univ. Artois, UR 4025, Laboratoire Systèmes Electrotechniques et Environnement (LSEE), F-62400 Béthune, France

<sup>2</sup>EOMYS ENGINEERING, Villeeneuve d'Ascq, France

<sup>3</sup>Univ. Lille, Arts et Métiers Institute of Technology, Centrale Lille, Junia, ULR2697-L2EP, Lille, France

This communication discusses the use of simulation for analyzing the vibro-acoustic behavior of radial flux electrical machines. The simulation enables a systematic investigation of electromagnetic Noise, Vibration and Harshness (e-NVH) issues, but requires accurate modeling and this despite real-world factors. Therefore, an experimental validation is necessary step for complex multiphysics problem such as e-NVH. In particular, a key point is the magneto-mechanical coupling. In this study, the Virtual Work Principle (VWP) is used for magnetic force calculation. The goal of this study is to propose an accurate e-NVH model for a 12s10p radial flux electrical machine using a mesh-to-mesh projection. This e-NVH model enables to understand the origin of the most noisy orders on the whole speed range of the machine. Moreover, the differences between simulation and experiments are analyzed thanks to the modal participation factor of specific harmonics.

*Index Terms*—electrical machines, virtual work principle, magnetic forces, mesh-to-mesh projection, vibrations.

## I. INTRODUCTION

THE analysis of the vibro-acoustic behavior of electrical machines is the subject of many research works [1]–[3]. The problem is even increased insofar as the mass and volume power optimization impacts the vibration and noise levels. These phenomena must be taken into account from the design stage based on multiphysics simulation. Simulation allows for a more controlled and systematic investigation of noise and vibration issues. It can be used to study the effect of various parameters on the acoustic performance of the machine. A key point of the model is the magneto-mechanical coupling.

In many related scientific works, the Maxwell stress tensor method is used to estimate the magnetic force distribution based on the airgap magnetic field. Then, the obtained magnetic force distribution can be projected onto the mechanical mesh (used for modal analysis) using a Galerkin mesh-to-mesh method [2], [4]. Indeed, the electromagnetic mesh of the stator is unsuitable and computationally costly to integrate into a complex FE model in order to perform the modal analysis fitting, compute e-NVH analysis, perform an optimization, etc.

However, the Virtual Work Principle (VWP) is a more accurate method to compute magnetic forces. This study proposes to perform a complete e-NVH simulation such as in [2], but using VWP instead of the Maxwell stress tensor method. Moreover, the study is performed on a 12s10p radial flux electrical machine specifically designed to study e-NVH issues [3].

Each simulation relies on accurate modeling of the system, which may not always be possible due to incomplete information or simplifications made in the model. In addition, simulation does not take into account real-world factors such as operating temperature, manufacturing tolerances and wear and tear on the machine, which can affect its performance. It is particularly the case for noise and vibration issues. Thus, an experimental validation is a necessary step to fully understand e-NVH phenomena, and in particular to validate the

magneto-mechanical coupling. This study proposes to validate the proposed e-NVH model by comparing experimental and numerical vibration levels at specific orders:

- at 2 times the electrical frequency,  $2f_s$ , because it is the frequency responsible for the high noise levels,
- and at 10 times the electrical frequency,  $10f_s$ , because it is responsible for the specific acoustic variation (resonances) during a run-up of the machine.

## II. NUMERICAL E-NVH MODEL

The simulations and analyses are performed on the 12s10p machine described in [3] in which only magnetic surface force are considered due to very low magnetic saturation. The magnetic field is solved using 2D non-linear magneto-static FE analysis with MANATEE-FEMM coupling [5]. The following steps are used to apply magnetic forces on the mechanical model: first compute magnetic nodal force with VWP on the magnetic mesh of the stator lamination, second compute the corresponding magnetic surface force density, third perform the Galerkin mesh-to-mesh projection of the force density onto the mechanical mesh, and finally compute nodal integrated force on the mechanical mesh nodes. The detailed algorithm steps can be found in [6] as well as the sensitivity study of the mesh-to-mesh projection parameters. The mesh-to-mesh projection is performed from the 2D magnetic mesh onto the 3D mechanical mesh: the 2D magnetic forces are considered uniform in the axial direction of the machine. The mechanical model is illustrated in Fig. 1 with the external vibrating surface and the loads on the stator lamination at  $2f_s$ .

The main magnetic force harmonic is at twice the electrical frequency  $2f_s$  and a resonance of  $10f_s$  with the ovalization modes (2,0) is also expected [3]. Hence, these harmonics are used to test the proposed approach of mesh-to-mesh projection, with the outputs of interest being the order tracking vibration levels at  $2f_s$  and  $10f_s$ . The ovalization of the stator yoke under magnetic forces at  $2f_s$  can be observed in Fig. 1.

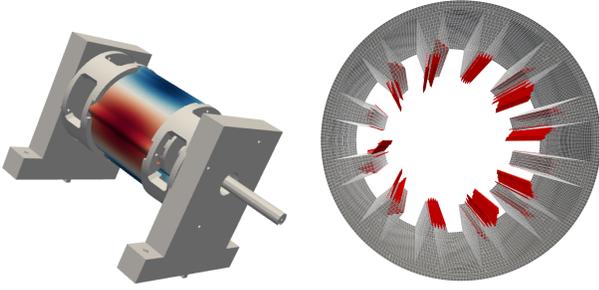


Fig. 1: Deflection shape (ovalization) of the stator at roation speed  $N = 550$  rpm, under corresponding magnetic force excitation at  $2f_s=92$  Hz.

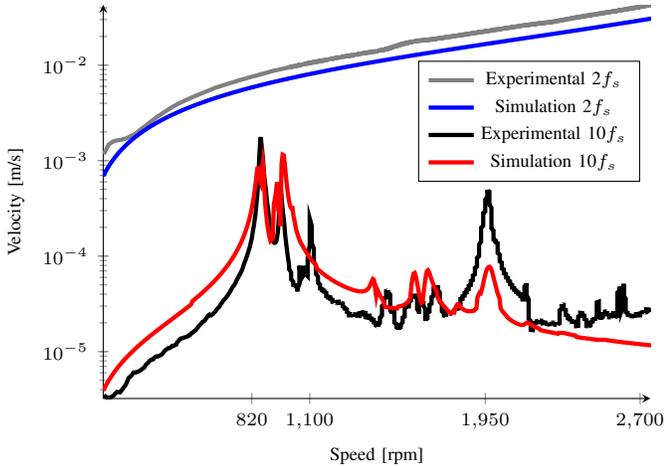


Fig. 2: Experimental run-up measurement compared to simulation using distributed nodal forces.

### III. EXPERIMENTAL VALIDATION

Measurements on the actual benchmark test-bed with the mounted 12s10p prototype have been performed. The comparison between numerical and experimental vibration RMS are presented in Fig. 2. The comparison at  $2f_s$  gives a good correlation between the simulation and the experiment with less than 1.5 dB of difference on the speed range. The comparison at  $10f_s$  gives also a good correlation with less than 3 dB error, except at the resonance around 1950 rpm where there is an error of 8 dB. This last resonance corresponds to the mode (3,0). In the numerical model, the unbalanced magnetic forces have been neglected, explaining the differences observed with simulation. It explains also the limited resonance on the experimental measurements at 1100 rpm: this mode has not been identified in the experimental modal analysis, but it could correspond to a bending mode of the experimental benchmark excited by non-uniform magnetic forces in the axial direction. Moreover, the numerical modal basis can be improved by working on the contacts model and damping fitting.

Further comparison can be done by using the modal projection factor which can be computed as a dot product between the normalized modal basis  $\mathbf{Q}_n$  corresponding to the  $n$ -th mode and the nodal force distribution [1]:

$$\left(\mathbf{Q}_n \cdot \hat{\mathbf{F}}\right)(\omega) = \sum_i \mathbf{Q}_n^i \hat{F}^i(\omega) \quad (1)$$

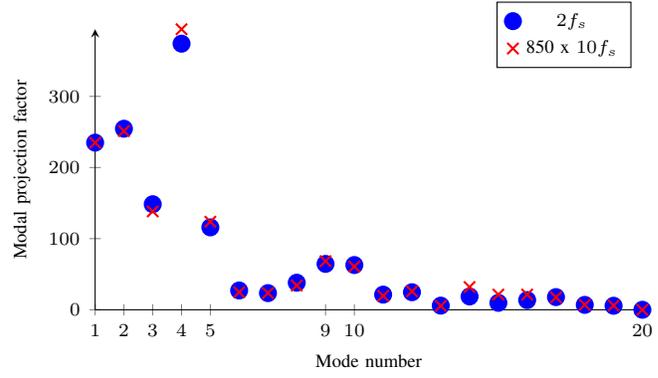


Fig. 3: Modal projection factor on each structural mode computed with numerical simulation.

The values of modal participation factors (1) are presented in Fig. 3. In both cases, the two main excited modes are the modes  $n^{\circ}2$  and  $n^{\circ}4$  which are symmetric (2,0) ovalization modes of the yoke at natural frequencies 727 Hz and 810 Hz to be compared with the experimental natural frequencies 721 Hz and 797 Hz of the same modes. Nevertheless, the numerical model excites secondary (2,0) modes ( $n^{\circ}1$  and  $n^{\circ}3$ ) which are not observed in experimental results of Fig. 2. The difference probably comes from inaccuracy for contacts in the FE model. This should be the subject of future research work. Finally, modes  $n^{\circ}9$  and  $n^{\circ}10$  correspond to (2,1) modes of the stator which are slightly excited despite the fact that the forces are constant in the axial direction of the machine. It can also be observed that the two harmonics  $2f_s$  and  $10f_s$  seem to have a proportional modal projection in Fig. 3: it means that despite the differences between magnetic both force distributions, the mechanical response is similar.

Although some differences remain between the numerical prediction and the experimental measurement, the proposed numerical model is accurate enough to be used as the reference to study the differences between the magnetic loading strategies (e.g. to validate a method based on Maxwell tensor approximation), or the effect of small design variation on the noise (e.g. shape of the teeth and magnets).

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