e-NVH Response Synthesis of Electric Motors Based on Stator Teeth FRF Measurements

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***Abstract*—The vibro-acoustic analysis of electrical machines under electromagnetic excitations (e-NVH) partly relies on the analysis of the stator response under Maxwell stress harmonic waves. In particular, the notion of unit-wave Frequency Response Function (FRF) is often used to diagnose magnetic noise issues during numerical simulations. However, such an FRF cannot be experimentally measured. This communication demonstrates the use of the stator tooth tip FRF which is compatible with both numerical and experimental approaches, and makes the link between tooth-excitation and wave-excitation based FRF. The two methods are compared in terms of physical insights and numerical aspects.**

***Index Terms*—Magneto-mechanical, electrical machine, vibration, magnetic force.**

I. Introduction

Noise and vibration prediction in electrical machine design (e-NVH) is of increasing interest with the widespread use of electric motors. Nevertheless, the magneto-mechanical coupling for numerical simulation is still an active research topic. In particular this communication focuses on the methods which allow to include Frequency Response Functions (FRF) [1] in the e-NVH process. The principle of the FRF is to characterize the response to a given load over a whole frequency range. The FRF can be performed through harmonic Finite Element Analysis (FEA) or experimental measurements. Not all the part of the electrical machine is excited by magnetic forces and the FRF of all nodes is not relevant. Thus the FRF efficiency depends on the loading strategy in electrical machines. In particular, the Wave FRF (WFRF) and the Tooth FRF (TFRF) are two methods used to model the response of an electrical machine to the magnetic force excitation [2]. In both methods a single magnetic Lumped Force per tooth (LF) is considered to load the structure.

The WFRF consists of loading all the teeth with a spatial excitation of wavenumber n. The WFRF is generally performed using one load vector per tooth. The WFRF method makes it easy to diagnose noise sources because it is generally possible to analytically determine wavenumbers created by the different electromagnetic sources [3]. However Wave FRF is hardly achievable through direct experimental measurement because wavenumbers cannot be isolated in electrical machines and it would be very complex to create an artificial sinusoïdal excitation. The TFRF consists of loading a single tooth per simulation, with generally a single load vector. The experimental Tooth FRF can be obtained by impacting any tooth with an impact hammer and measuring its external yoke vibration response with an accelerometer normalized by the injected force.

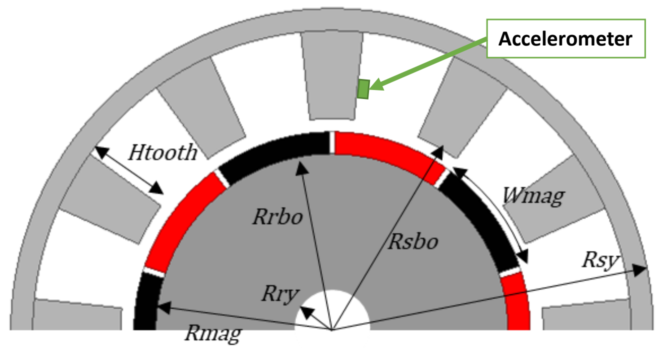

Fig. 1. Prototype 12S10P SPMSM for experimental validation

This communication proposes a new method which enables to generate an artificial WFRF based on the results of the TFRF method. This new method is called Tooth Wave FRF (TWFRF). The main interest of the TWFRF is to allow the import of experimental tooth excitation in order to numerically simulate the vibrations and noise emitted by the machine during operation. In order to validate the method, this communication presents the experimental protocol to measure TFRF on a testbench designed to illustrate the interaction between magnetic forces and the structural of electrical machines. The geometrical data of the studied stator are presented in Table I and in Fig. 1.

II. Frequency Response Functions

A. Magnetic forces

This section presents the computation method of magnetic lumped tooth forces (LF) for the magneto-mechanical coupling. The method considers that the stator is excited with an airgap radial surface force density wave σ_r computed on a circular contour on the stator bore radius R_{sbo} for the angular position $\alpha \in [0, 2\pi]$ at time t such that the force wave can be decomposed into:

$$\sigma_r(\alpha, t) = \sum_n \sum_\omega \sigma_r(n, \omega) e^{jn\alpha} \quad (1)$$

with j the imaginary number, ω the frequency, n the wavenumber. This airgap surface force wave can be computed using the airgap Maxwell Tensor method [4]. The next step is to integrate σ_{r} on a slot pitch $\frac{2\pi}{Z_s}$ to get $F_{r,i}$ which is the corresponding LF on the i$^{\mathrm{th}}$ tooth at angular position α_i:

$$F_{r,i}(t) = \int_{\alpha_i - \frac{\pi}{Z_s}}^{\alpha_i + \frac{\pi}{Z_s}} \sigma_{\mathrm{r}}(\alpha, t) \cos(\alpha_i - \alpha) \, \mathrm{d}\alpha \tag{2}$$

B. Wave Frequency Response Functions

This section presents the WFRF model with lumped tooth forces (LF). Assuming the mechanical linearity, each wavenumber n can be considered independently. Then the simulation of a limited number of spatial wavenumber allows to significantly reduce the computation time [2]. Thus it is interesting to consider a single airgap force wave amplitude injected in (2) to get the corresponding spectral LF on the i$^{\mathrm{th}}$ tooth [3]:

$$F_{r,i}(n, \omega) = \mathrm{R_{sbo}} \mathrm{L_{st1}} \frac{2\pi}{\mathrm{Z_s}} \sin(n \frac{\pi}{\mathrm{Z_s}}) \sigma_{\mathrm{r}}(n, \omega) \mathrm{e}^{jn\alpha_i} \tag{3}$$

Then several harmonic FEA simulations are performed depending on the wavenumbers n of interest with all teeth loaded according to (3). The injected amplitude is generally a unit airgap surface force wave $\sigma_{\mathrm{r}}(n, \omega) = \mathrm{e}^{j\omega + \phi_{n,\omega}}$ for a given range of frequency ω such that the output is normalized. The external yoke complex displacement per wavenumber $Y_n(\omega)$ is the output value of interest.

C. Tooth Frequency Response Functions

The TFRF method is based on the linearity of the mechanical behaviour. Only one tooth is loaded with a unit airgap surface force wave $\sigma_{\mathrm{r}}(n, \omega) = \mathrm{e}^{j\omega + \phi_{n,\omega}}$. The number of simulations to be performed depends on the symmetry properties. In particular, if the tooth pattern repeats itself over space such as in Fig. 1, only one simulation is necessary since all the teeth would have the same mechanical behaviour.

The TFRF is obtained experimentally by impacting a tooth with an impact hammer and measuring external yoke structural response with an accelerometer normalized by the injected force. However this protocol can be difficult to apply if the teeth are difficult to access (small engine, engine already assembled). Alternative protocol relies on the reciprocity theorem [1]: the experimental TFRF can be determined by hammering the external yoke and measuring the vibration on the tooth with an accelerometer. The external yoke complex displacement per tooth $Y_i(\omega)$ with $i \in [1, \mathrm{Z_s}]$ is the output value of interest.

The immediate result of the TFRF is unsuitable for understanding the main sources of vibrations - therefore noise - of magnetic origin. Indeed the electromagnetic components do not excite a particular region of the machine but rather in the form of a rotating force wave such as (1). Thus the following section proposes to synthesize a WFRF from the results - experimental or numerical - of a TFRF.

TABLE I
BENCHMARK PROTOTYPE PARAMETERS.

Parameter	**Symbol**	**Value**
Number of stator teeth	$\mathrm{Z_s}$	12
Stator bore radius	$\mathrm{R_{sbo}}$	48 [mm]
Stator yoke height	$\mathrm{H_{sy}}$	5 [mm]
Stator tooth length	$\mathrm{H_{tooth}}$	20 [mm]
Stator outer radius	$\mathrm{R_{sy}}$	73 [mm]
Stator stack length	$\mathrm{L_{st1}}$	140 [mm]
Stator slot width	$\mathrm{W_s}$	18 [degrees]
Stator lamination		M400-50A

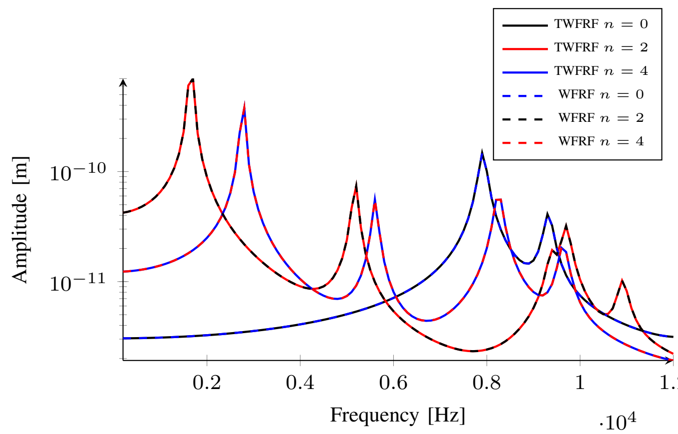

Fig. 2. Comparison of RMS value for WFRF and TWFRF methods for several excitation wavenumbers

D. Tooth Wave Frequency Response Functions

Considering the TFRF $Y_i(\omega)$ for $i \in [1, \mathrm{Z_s}]$, the response to a sinusoidal excitation of order n is reconstructed a posteriori:

$$Y_n(\omega) = \sum_{i=1}^{i=Z_s} Y_i(\omega) \; \mathrm{e}^{jr\alpha_i} \tag{4}$$

This reconstruction is called the TWFRF. The method is numerically validated through FEA using MANATEE-Optistruct coupling [2] as illustrated in Fig. 2. As expected there is a perfect match between the WFRF and the TWFRF since the mechanical simulation was performed with linear FEA. In the extended paper, an experiemental TFRF measurement will be carried out with an accelerometer placed as in Fig. 1. These measurements will allow to compute the TWFRF. Then the vibroacoustic behaviour in operation will be predicted using MANATEE. The method will be validated by comparing the results with vibroacoustic measurements in operation.

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