A Fast and Accurate Multi-Physic Approach to Predict Acoustic Noise: Application to SRMs

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***Abstract*—Vibration and acoustic noise can constitute a serious problem in electric machines. They are mainly caused by the deformation of the stator lamination stack due to its magnetic attraction to the rotor. This paper presents a 2D multi-physic tool which permits to predict electromagnetic acoustic noise generated by electric motors, since the early design phase. This tool is based on 2D magnetic, vibration and acoustic models and the final goal is to find the best compromise between accuracy and calculation time. The magnetic model is based on the Finite Element (FE) method in order to take into account nonlinearities, especially for SRMs which are usually highly saturated. The vibration and acoustic models are calculated through analytic approaches. The analytical results are then compared to those of a full FE approach for an 8/6 SRM and good agreements are obtained.**

***Index Terms*—Vibrations, Acoustic noise, Magnetic noise, Magnetic forces.**

I. INTRODUCTION

Acoustic noise sources in electric machines can be divided into three parts: electromagnetic, mechanical and aerodynamic. In the case of Switched Reluctance Motors (SRMs), many studies have shown that the electromagnetic radial forces acting on the stator are the dominant source of vibration and acoustic noise [1]-[2]. When a phase is excited, the magnetic flux from the excited stator pole crosses the air gap in a radial direction producing large radial force. If there is coincidence in frequency and shape between radial forces and the structure modal behavior, resonance occurs, leading to particularly strong vibrations and consequently high acoustic levels.

II. 2D MULTI-PHYSIC MODELS

In order to be able to predict the noise level of an electric motor, electromagnetic and mechanical models are needed. Mainly, two different methods exist: Analytical and FE methods. The FE method gives accurate results, but is quite time-consuming. The analytical method, on the contrary, is less accurate because of the introduction of many hypothesis and simplifications, but it is quicker. The aim of this study is to achieve the best compromise between accuracy and time-consumption. Hence, the radial magnetic forces are calculated by FE method in order to take into account the nonlinear electromagnetic behavior (Saturation especially for SRMs). The vibration and acoustic models are based on analytical calculation.

A. Magnetic model

The radial forces in a machine are directly proportional to the square of the flux density in the air gap. This later data is obtained through FE modeling taking into account the nonlinear (B-H) curve. An 8/6 SRM is modeled using Maxwell2D software. Due to the symmetry, only half of the motor has been modeled as shown in Fig. 1.

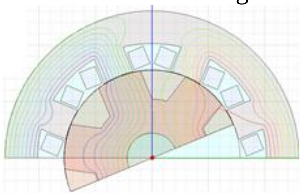


Fig. 1. An 8/6 SRM electromagnetic model

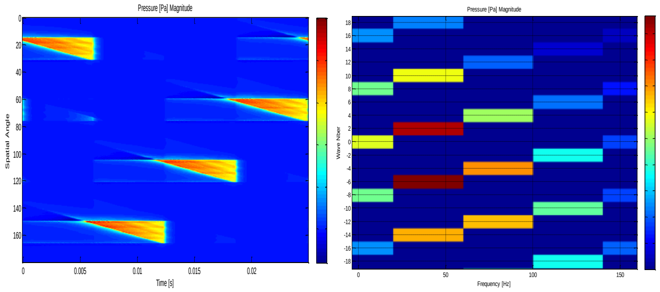
The resolution method is based on the quasi-static magnetic potential vector formulation. In the middle of the air-gap, the radial Maxwell pressure acting on the stator is computed by:

$$P_r(t,\theta) = \frac{B_r^2 - B_t^2}{2\mu_0} \tag{1}$$

For a constant speed, the radial magnetic pressure as a function of time and space is presented on Fig. 2(a). In order to inject this Maxwell pressure in the vibration model, a bi-dimensional (space and time) Fast Fourier Transform (FFT) is needed. It can then be decomposed as a sum of sinusoidal travelling waves:

$$P_r(t,\theta) = \sum_i A_i \cos\left(2\pi f_i t - k_i \theta + \varphi_i\right) \tag{2}$$

Where A_i , f_i, k_i and φ_i are respectively the magnitude, frequency, wave number and phase-shift of the different travelling waves. The color scale in Fig. 2(b) shows the magnitudes of the waves as a function of frequencies and wave numbers.



(a) Before FFT (b) After FFT

Fig. 2. Electromagnetic Maxwell pressure

B. Vibration model

In this paper, the deformation of the stator is approximated by the deformation of a circular beam (Ring). To calculate the natural frequencies and the dynamic vibration response of this ring, its equilibrium (Fig. 3) is studied and leads to two differential equations of motion for flexure and extension vibrations. The expressions of the natural vibration angular frequencies are given by:

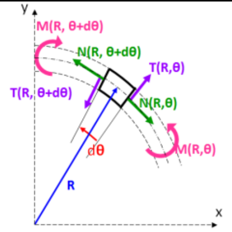


Fig. 3. Ring Equilibrium

Mode angular frequencies	
Flexure	Extension
$\omega_n^2 = \dfrac{EI}{\rho A R^4}\dfrac{n^2\left(n^2-1\right)^2}{\left(n^2+1\right)}$	$\omega_0^2 = \dfrac{E}{\rho R^2}$
E, ρ : Stator Young’s modulus and density R, A, I: Ring’s mean radius, section and area moment of inertia	

These expressions can be found in the literature [3]-[4]-[5]. In this work, the analytical relation for the ring vibration response under a sinusoidally distributed load, is calculated:

$$U(t,\theta) = \sum_i C_i^u \cos\left(\omega_i t - k_i\theta + \varphi_i\right) \tag{3}$$

Where U is the radial vibration displacement and C_i^u is the vibration modal contribution factor.

C. *Acoustic Model*

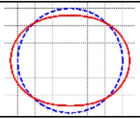
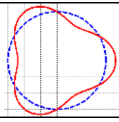
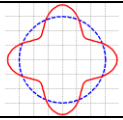
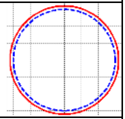
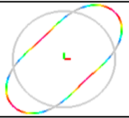
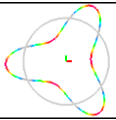
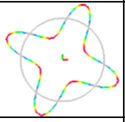
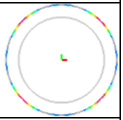
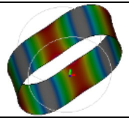
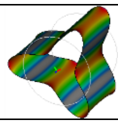
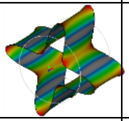
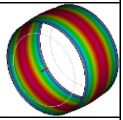
In order to estimate the acoustic pressure generated by the stator, the Helmholtz equation is established in a cylindrical coordinate system. The general solution of this equation is calculated in [6]. Once adapted to our case (velocity continuity between structure and fluid and Sommerfeld condition), it leads to the expression below:

$$p(r,t,\theta) = \sum_i D_i(r)\cos\left(\omega_i t - k_i\theta + \varphi_i\right) \tag{4}$$

Where p is the acoustic pressure and D_i is the acoustic modal contribution factor. D_i decreases with distance from the source with $1/\sqrt{r}$ relationship due to the Hankel function of the second kind.

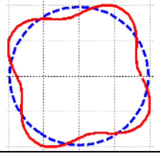
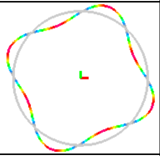
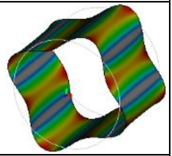
III. COMPARISON BETWEEN ANALYTICAL AND FINITE ELEMENT METHOD MODELS

To verify the validity of the above vibration relations, the analytical results are compared to 2D (Ring) and 3D (Cylindrical shell) FE models. The natural frequencies and the dynamic vibration response are obtained from FE calculations using the simulation software NASTRAN and then compared to those resulting from the analytical model, as shown below:

		Mode n = 2	Mode n = 3	Mode n = 4	Mode n = 0
Analytical	Mode shapes				
	f_n	997 Hz	2820 Hz	5407 Hz	8367 Hz
FE 2D	Mode shapes				
	f_n	994 Hz	2811 Hz	5388 Hz	8367 Hz
	Error 2D	0.3 %	0.3 %	0.3 %	0.0 %
FE 3D	Mode shapes				
	f_n	1011 Hz	2817 Hz	5296 Hz	8266 Hz
	Error 3D	1.4 %	0.1 %	2.0 %	1.2 %

This table shows that the FE results, in terms of frequencies and mode shapes, are quite similar to those analytically predicted and the biggest relative error is about 2%.

Then, a theoretical electromagnetic pressure travelling wave (wave number = 4 and frequency = f_4) is applied to the analytical and the FE mechanical models so that the vibration response can be calculated. In this case, frequency and spatial coincidence leads to resonance. The table below shows the comparison between analytical and FE radial displacement:

	Analytical	FE 2D	FE 3D
Dynamic response			
U_{max} (mm)	7.15E-2	7.11E-2	6.97E-2
Error	---	0.5 %	2.5 %

The next step consists in the validation of the analytical acoustic model with 2D and 3D FE models built using ACTRAN.

IV. CONCLUSION AND FURTHER WORK

This paper presents a 2D multi-physic tool allowing the prediction of the electromagnetic noise level generated by electric machines, since the early design phase. The challenge being the best compromise between accuracy and calculation time, this tool combines FE and analytical methods. The originality of the proposed approach lies on the analytical dynamic response calculation and its comparison with FE results. The tool is applied to an 8/6 SRM in order to understand and quantify its advantages and limitations.

In the extended version, a study with a more “realistic” 3D-toothed stator structure shown in Fig. 4 will be carried on, using the FE electromagnetic pressure presented in Fig. 2. By comparing its results to the analytical results, stator length and teeth effects will be quantified.

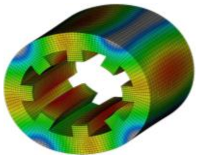


Fig. 4. 3D FE vibration results of an 8/6 SRM stator

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