Prediction of Noise Generated by Electromagnetic Forces in Induction Motors

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Abstract: Induction motors, as any other industrial products, have to comply with various requirements on noise levels. Therefore, it is essential to use an appropriate prediction tool to verify and optimize the design of an induction motor with respect to the acoustic performances. The paper will focus on the prediction of the magnetic noise generated and radiated by a specific motor. The challenge is here in the multi-disciplinary character of the problem. The model should consider the mutual coupling between electromagnetic forces, the displacements and the acoustic pressure field.
The finite element model coupling the different physical fields has been developed by using COMSOL. Some simplifications have been introduced to reduce the problem size and computing time.

Keywords: Induction motor, electromagnetic forces, acoustics

1. Introduction

Today, the limitation of noise pollution is a matter of increasing importance in a world where the number of equipment generating sound and vibrations is steadily growing. Therefore, low noise levels are mandatory for many industrial products to comply with customer requirements and environmental regulations. Consequently, it is essential to predict the sound levels of induction motors with a sufficient accuracy at an early stage of the product design to select the most appropriate strategy for noise control.

Three main sources of sound can be identified in induction motors: mechanical noise from bearings and unbalance effects, airflow noise due to the cooling fan and magnetic noise produced by electromagnetic forces in the motor air gaps.

The paper describes a prediction method for electromagnetic noise which constitutes a typical multiphysics phenomenon involving three physical fields: electromagnetism, mechanics and acoustics. The interaction between the alternating electrical supply and the associated rotating magnetic fields results in varying forces generating structural vibrations which eventually are radiated as sound in the surrounding environment.

In some cases, analytical models can be used advantageously to provide a rather quick indication of the sound levels generated by induction motors. However, in general, due to the relative complexity of the motor geometry, this approach may present limitations for detailed investigations. Therefore, prediction models based on finite element formulation shall be applied to describe accurately the complex interactions of the various design parameters and the coupling of the physical fields.

In this paper, an overview of the modeling procedure is first given in section 2. Then, the governing equations for the electromagnetic, mechanical and acoustic fields are described in sections 3, 4 and 5. Some predicted results are reported and discussed in section 6.

2. Modeling Procedure Overview

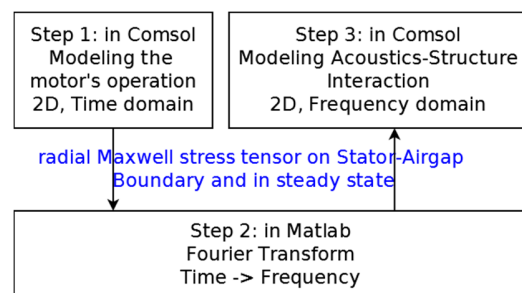The prediction of electromagnetic noise from an induction motor is performed in 3 steps.

Figure 1. Overview of the three modeling steps.

In the first step, the motor is modeled in 2D and in time domain until it reaches steady state where it exhibits a stabilized harmonic pattern. In step 2, the magnetic forces (the radial Maxwell stress tensors in this study) are extracted from COMSOL into Matlab for the steady state along the stator's inner surface. The magnetic forces are then transformed by means of Fourier analysis

from time domain into frequency domain. In the third step, the stator is modeled with surrounding air in 2D and frequency domain in COMSOL. In this step, the Acoustic-Structure interaction is investigated to predict the noise level of the motor. Fig. 1 gives an overview of the modeling steps.

3. Step 1: The Motor Operation

The operating motor is modeled in 2D with the combination of finite element method and electrical circuits (lumped element method), as described in [1] and [2].

Electromagnetic field:
The lamination effects in the rotor and stator's cores are assumed to be perfect. The stator coils are assumed to be made of thin wires so that no eddy currents are assumed to be present. The equations for the motor domains, as presented in [3], are given by

$$\nabla \times (\nu \nabla \times \mathbf{A}) = \begin{cases} \frac{N_w I_w}{S_w} \mathbf{e_z} \text{ in stator slots} \\ -\sigma \frac{\partial \mathbf{A}}{\partial t} + \sigma \frac{V_b}{l_b} \mathbf{e_z} \text{ in rotor bars} \\ -\sigma \frac{\partial \mathbf{A}}{\partial t} \text{ in shaft} \\ 0 \text{ in cores and air} \end{cases}$$

(1)

where $\mathbf{e_z}$ is the unit vector pointing in the z-direction, $\mathbf{A} = A_z \mathbf{e_z}$ the magnetic vector potential. N_w, I_w, S_w are the number of turns, current and cross-section area of a slot. V_b, l_b are the voltage and length across a rotor bar. σ is the electrical conductivity of the domain materials.
In COMSOL, the electromagnetic field is modeled using Rotating Machinery, Magnetic (rmm) interface. The stator slots domain are modeled by Multiturn Coils which are excited by current from external circuit. Rotor bar domains are modeled with SingleTurn Coil which are excited by voltage from external circuit.
The rotor domain and half of the airgap is rotated using Prescribed Rotation.

Stator circuit equations:
In the stator circuit, the end winding of each phase is represented by an inductor and a resistor. The coil sides are lumped into one resistor.
A sample of the circuit for phase A is shown in Fig. 2.
By Kirchhoff's voltage law, the equation for the loop in Fig. 2 is

$$V_A = V_{emf} + R_c I_A + L_e \frac{dI_A}{dt}$$

(2)

where V_A is the voltage of phase A, I_A the current in the loop, R_c the coil's resistance (including the end winding), L_e the end winding inductance. V_{emf} is the total induced voltage across the coil sides (the parts of the coil in the stator core region).

$$V_{emf} = \frac{N_s l_s}{S_s} \left(\int_{\mathbf{A+}slots} \frac{dA_z}{dt} dS - \int_{\mathbf{A-}slots} \frac{dA_z}{dt} dS \right)$$

(3)

where N_s, l_s, S_s are the number of turns, stator length and cross-section areas of the stator slots. A_z is the magnitude of the magnetic vector potential in z-direction.
$\mathbf{A+}slots, \mathbf{A-}slots$ indicate the slots where the currents are in $\mathbf{e_z}$ and $-\mathbf{e_z}$ directions, respectively, depending on the selected convention.
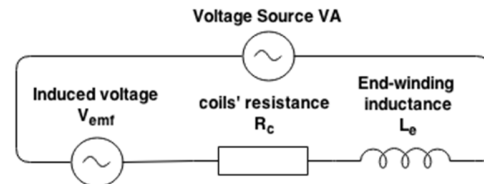

Figure 2. A sample of stator circuit for one phase.

The stator circuit is modeled by the Electrical Circuit in COMSOL. To couple with the rmm interface, the induced voltage is modeled by the External I vs U component.

Rotor circuit equations:
Each segment of the end ring is represented by an inductor and a resistor [1]. The extra part of the bars outside the core is lumped into one resistor at each end. Fig. 3 shows the circuit for the rotor.
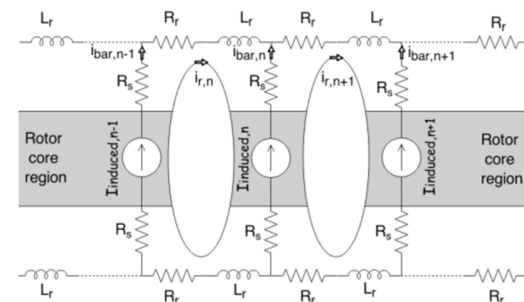

Figure 3. The rotor circuit.

By Kirchhoff's voltage law, the voltage equation for loop of $i_{r,n}$ is expressed as

$$V_n - V_{n+1} + 2R_s(i_n - i_{n+1}) + 2R_r i_{r,n+1} + 2L_r \frac{di_{r,n+1}}{dt} = 0 \qquad (4)$$

where V_n is the voltage across the nth bar in the rotor core region and i_n is the nth bar's current. R_s is the resistance of the bar outside the rotor core region at one end. R_r, L_r are the resistance and inductance of one ring segment.

Kirchhoff's current law gives

$$i_n = i_{r,n+1} - i_{r,n} \qquad (5)$$

where $i_{r,n}$ is the current in the nth ring.
The nth bar's current is:

$$i_n = -i_{induced,n} + \frac{V_n}{R_n} = -\sigma \int_{S_n} \frac{\partial A_z}{\partial t} dS + \frac{V_n}{R_n} \quad (6)$$

where V_n, R_n are the voltage and the resistance of the nth bar, σ is the electrical conductivity of rotor bars and S_n is the cross section of the nth bar.

The rotor circuit is modeled by the Electrical Circuit in COMSOL. To couple with the rmm interface, the induced current is modeled by the External U vs I component.

Rotation equation:
The rotational angle of the rotor is expressed by

$$J \frac{d^2\alpha}{dt^2} = T_{rotor} - T_{load} \qquad (7)$$

where J is the moment of inertia of the rotor and α the rotational angle. T_{rotor} and T_{load} are the rotor and load torques, respectively.
Equation (7) is implemented by the Global ODEs and DAEs interface in COMSOL.

Summary:
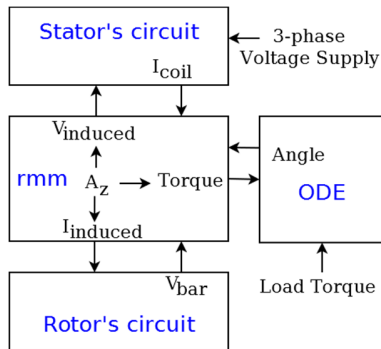The relationship between the COMSOL interfaces in step 1 is shown in Fig. 4.

Figure 4. Relationship between COMSOL interfaces in the model in step 1.

3. Step 2: Fourier Transform

The operating mode of the motor is simulated until the steady state is reached, as the motor exhibits harmonic behavior.
The radial Maxwell stress tensor is extracted from COMSOL to Matlab during the steady state along the boundary between the stator and air gap, then transformed into frequency domain for the acoustic analysis.

4. Step 3: Acoustic-Structure Interaction

The forces applied on the stator generate a displacement field which in turn implies a sound wave in the air surrounding the structure. In this model, only the motor stator and housing are taken into account. Air is modeled between the stator and housing as well as around the housing. The density of the air ρ_A is assumed to be constant. The four equations used to describe the acoustic-structure interaction in the frequency domain are given by

$$-\rho_S \ddot{\mathbf{u}} = \nabla \cdot \sigma + \mathbf{F_V} \text{ in stator}$$
$$\frac{1}{c^2}\ddot{p} - \nabla^2 p = 0 \text{ in air}$$
$$\frac{1}{\rho_A}\mathbf{n} \cdot (\nabla p) = -\mathbf{n} \cdot \ddot{\mathbf{u}} \text{ at stator-air boundary}$$
$$\sigma \cdot \mathbf{n} = p\mathbf{n} \text{ at stator-air boundary}$$
$$(8)$$

The first equation is derived from Newton's second law where ρ_S is the density of the structure, $\mathbf{u}$ the displacement vector, σ the stress tensor, $\mathbf{F_V}$ the body force.
In the second equation, p is the sound pressure and c the speed of sound in air.
The last two equations show the continuity of the acceleration and pressure in the normal direction to the Structure-Air boundary.
The radial Maxwell stress tensor obtained in the frequency domain is applied on the stator's inner surface.
The Acoustic-Structure interaction is solved in frequency domain. Therefore the above equations are to be transformed to frequency domain. In COMSOL, the modeling is done by the Acoustic-Solid Interaction, Frequency interface. Air is built around the case for noise investigation. The outermost layer of the air is defined as Perfectly Matched Layer (PML) to absorb the sound radiated from the stator and create free field conditions for propagation of sound waves. In

addition, structural damping are implemented in the motor stator and housing.

4. Modeling Parameters

A specific motor is modeled in COMSOL in this study and the parameters used for the simulations are presented in Table 1.

Table 1. Motor parameters

Power supply	3 phase, 388V (nominal)
Number of poles	4 poles
Stator	48 slots
Rotor	Squirrel cage, 38 straight bars
Load	No load

Parameters used for the solver in order to model the operating motor are shown in Table 2.

Table 2. Solver parameters for step 1.

Method	Generalized alpha
Time step	Fixed (0.0001s)
Nonlinear solver	Newton method

6. Prediction Results

The 2D model of the motor described in section 4 was created and run according to the procedure explained in section 2. The calculations were performed at the electrical frequency of 50 Hz corresponding to a rotation speed of 1500 rpm for the motor. The total force amplitudes obtained by integration of the Maxwell stress tensor on the stator-airgap line at each frequency are given in Fig. 5.
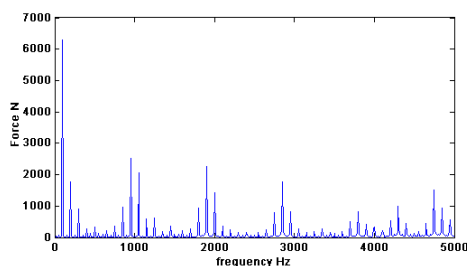

Figure 5. The total electromagnetic forces with respect to frequency.

To explain the acoustical behaviour of the motor, the mode shapes of the motor are determined in 2D by using the solid mechanics interface in COMSOL. Neither air is present, nor external forces are applied on the stator in this particular model. A few mode shapes calculated for the stator with housing and the stator without housing are shown in Fig. 5. The different resonance frequencies obtained for both configurations are presented for the same mode shapes.
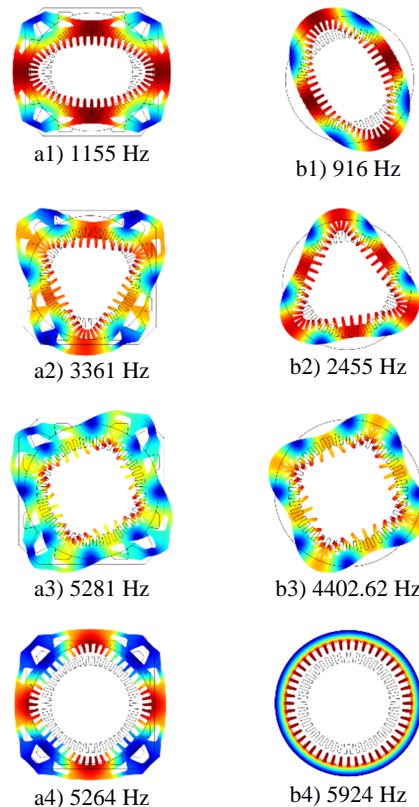

a1) 1155 Hz   b1) 916 Hz

a2) 3361 Hz   b2) 2455 Hz

a3) 5281 Hz   b3) 4402.62 Hz

a4) 5264 Hz   b4) 5924 Hz

Figure 6. Mode shapes of stator with housing (a1-a4) and stator without housing (b1-b4).

The electromagnetic forces applied on the motor structure consisting of stator and housing provide the sound power level presented in Fig. 7. The clear peak observed at 1150 Hz in the sound power level plot corresponds to an amplification implied by the resonance identified at 1155 Hz, as shown in Fig. 6. As a matter of fact, the total force at 1150 Hz does not present a particularly high level in Fig. 5. However, it can still provide the main contribution to the total sound power level when it is combined with a resonance.

Sound pressure and displacement fields are displayed for the stator with housing at 1150 Hz in Fig. 8. In this picture, the mode shape of the motor determined at 1155 Hz can be clearly identified.
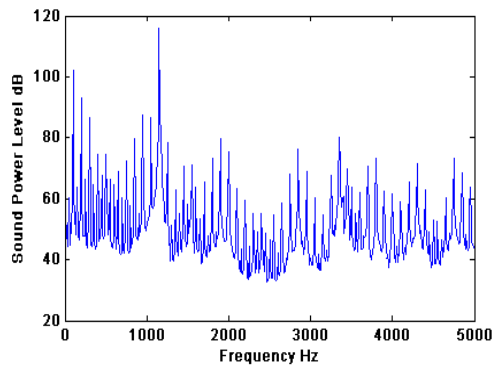
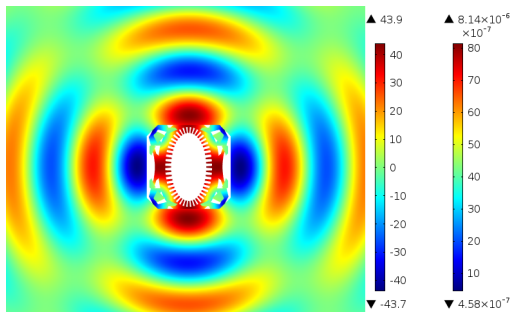**Figure 7.** Sound Power Level for the motor operating at 1500 rpm.

Figure 8. Total Sound Pressure field (root mean square) and displacement field. The color bar on the left is for the pressure (in Pa) and on the right is for the displacement (in m).

7. Conclusions

A method for predicting the noise levels generating by an induction motor was presented. The electromagnetic FE-model of the motor is first solved in the time domain, then the resulting forces are transformed to the frequency domain in order to perform the acoustic analysis.

It was demonstrated that the motor operating at 1500 rpm is particularly noisy at the particular frequency of 1150 Hz close to a natural frequency identified at 1155 Hz.

The prediction tool can already be used to investigate the impact of various design parameters on the sound power levels.

The present work will be continued by extruding the 2D mechanical model into a 3D model in order to perform more accurate investigations and validate the predicted results with experimental data.

8. References

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9. Acknowledgements