Prediction of Transformer Core Noise

R. Haettel[*,1], M. Kavasoglu[1], A. Daneryd[1] and C. Ploetner[2]
[1]ABB Corporate Research Sweden, [2]ABB Transformers Canada
*Corresponding author: 721 78 Västerås Sweden, romain.haettel@se.abb.com

Abstract: Low noise is nowadays a mandatory feature for power transformers in order to comply with customer specifications and environmental regulations. Therefore, it is crucial to develop sound prediction tools with sufficient accuracy to avoid on one side overkill margins in design and on the other side costly modifications after transformer completion.
The paper will focus on the so called core noise which is a typical multiphysics mechanism involving electromagnetism, mechanics and acoustics. The finite element model coupling the different physical fields has been developed by using COMSOL.
Some simplifications have been introduced to reduce problem size and computing time. The prediction model provides a rather accurate tool to perform parametric studies. In the paper, the modeling procedure is described and results from parametric studies are presented.

Keywords: Transformer, core, acoustics

1. Introduction

Transformers shall comply with various requirements on noise levels [1,2]. Consequently, manufacturers have to guarantee the acoustic performances of their products, while, at the same time, limiting the costs. It is thus of great importance to predict sound levels with a sufficient accuracy at an early stage of the product design.
There are three main sources of noise in transformers: core noise generated by magnetostriction in the core steel laminations [3], load noise produced by electromagnetic forces in the windings [4] and auxiliary equipment noise due to fans and pumps of the cooling system.
The paper describes a method to predict core noise which constitutes a typical multiphysics phenomenon involving electromagnetism, mechanics and acoustics. When an alternating voltage is applied to one or more windings of a transformer, a magnetic flux is generated in the transformer core laminations made of grain oriented electrical steel. This material has a non-linear anisotropic property called magnetostriction implying alternating changes of the core dimensions due to the varying magnetic flux in the laminations. Those magnetostrictive forces cause core vibrations which are transmitted to the tank via the insulation oil and the core clamping points. Part of the mechanical energy is eventually radiated by the tank walls as noise.

Due to the complexity of the structure and the strong coupling with oil, an analytical model cannot be used to predict the sound radiation. In general, empirical methods based on statistics and dimensional basic parameters are used by most transformer manufacturers. This approach presents limitations when applied to new designs and does not enable accurate parametric studies. Therefore, prediction models based on finite element formulations shall be utilized to describe accurately the complex interactions of the various design parameters and the coupling of the physical fields.

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

2. Electromagnetic Model

At no-load condition, an alternating voltage is applied to the phase windings on one side of the transformer while the windings on the other side (usually called primary side) are left open. The primary windings will carry the magnetizing current and a magnetic flux will be induced in the core.
To obtain the magnetic flux density in the core at no-load, Maxwell's equations are used with the additional expressions.

$$\mathbf{B} = \mu \mathbf{H} \tag{1}$$

where μ is the magnetic permeability in the core material and $\mathbf{H}$ the magnetic field strength.

$$\mathbf{J} = \sigma \mathbf{E} \tag{2}$$

where **J** is the current density and **E** the electric field density.
The resulting magnetic flux density **B** induced by the total currents (Ampere turns) of the windings can be expressed as

$$\mathbf{B} = \nabla \times \mathbf{A} \tag{3}$$

where **A** is the magnetic vector potential.
By combining Maxwell's equations and the vector potential formulation, the governing equation for the magnetic field is given by the relationship

$$\sigma \frac{\partial \mathbf{A}}{\partial t} + \nabla \times \left(\frac{\nabla \times \mathbf{A}}{\mu} \right) = \mathbf{J} \tag{4}$$

The model is investigated in two dimensions by considering one single core package at a time. The core is surrounded by air. A magnetically insulating boundary condition is used on the outer boundary imposing the constraint

$$\mathbf{n} \cdot \mathbf{H} = 0 \tag{5}$$

where the normal component of the magnetic field is set to zero.
Experimental data for a specific steel type are used in the model to describe the magnetic properties of the core material. The core steel sheets are magnetically oriented and the permeabilities in the rolling and cross-rolling directions present different non-linear virgin curves, as shown in Fig. 1.

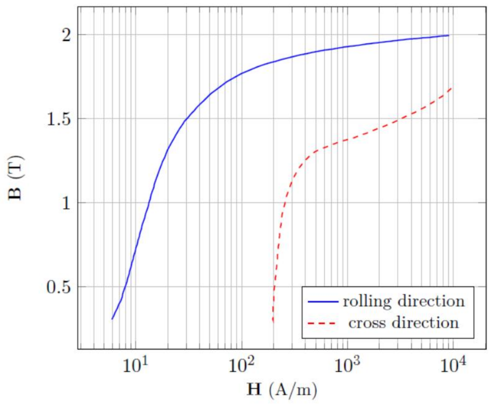

Figure 1. Permeabilities in rolling and cross-rolling directions for the core steel sheets.

The excitation is provided by voltages shifted by a phase of 120º applied to the windings to simulate a three phase transformer. The analysis is then carried out in the time domain to obtain a magnetic field density in the core, as displayed in Fig. 2.

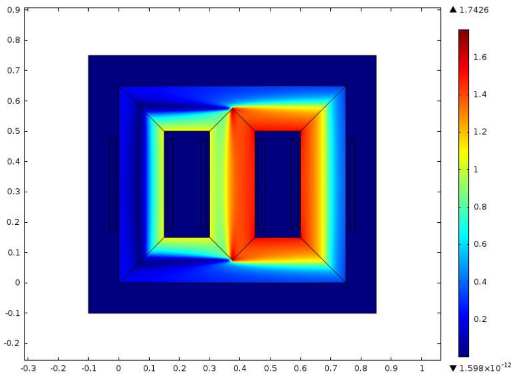

Figure 2. Magnetic flux density distribution in Tesla for a three phase transformer core at one specific point on wave.

The time signals of the magnetic field density calculated in the middle of each limb are presented in Fig. 3 when the harmonic state is reached.

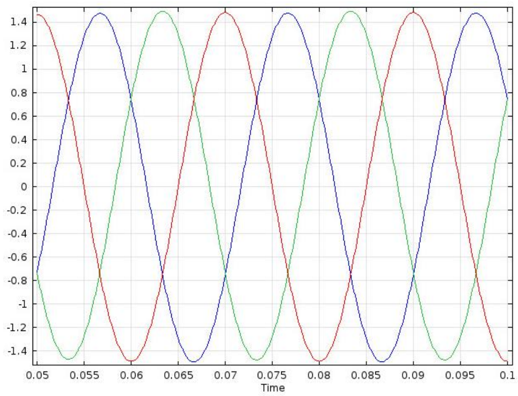

Figure 3. Magnetic flux density in Tesla in the middle of the three limbs with respect to time.

By applying a Fast Fourier Transform to the time signals, the main frequency components of the magnetic flux density in rolling and cross rolling directions can be calculated at each node point of the mesh. The fundamental magnetic components at each node can then be systematically associated with magnetostrictive strains provided in tables

gathering experimental data specific for each steel grade, as shown in Fig. 4.
Those values relating magnetic field and magnetostrictive strains are used as input data to the mechanical simulations performed in the frequency domain.

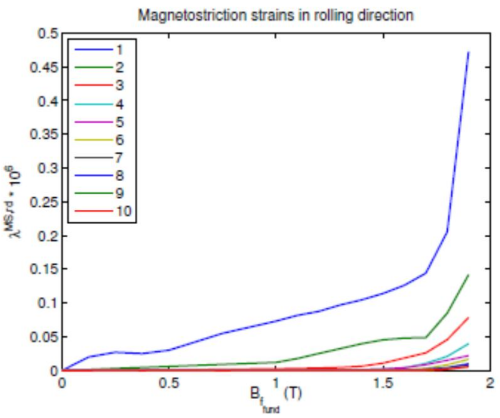

Figure 4. Magnetostriction strains with respect to induction in rolling direction for the fundamental frequency and nine harmonics.

3. Mechanical Model

In the mechanical model, the linear elasticity equations are used to describe the in-plane motion of the core implied by the magnetostrictive strains. The Navier's equation is given by the expression

$$\nabla \cdot \sigma = -\mathbf{F}_{\mathbf{v}} \quad (6)$$

where σ is the stress tensor and $\mathbf{F}_{\mathbf{v}}$ the volume forces.
The stress tensor σ is a function of the strain tensor ε^{mech} as given in Hooke's law

$$\sigma = E \cdot \varepsilon^{mech} \quad (7)$$

Where E is the elasticity tensor.
Since the electric steel has different elasticity properties in rolling and cross rolling directions, the elasticity tensor is specified for an orthotropic material. Then, the magnetostriction strain is introduced into Hooke's law

$$\sigma = E \cdot (\varepsilon^{mech} - \varepsilon^{mag}) \quad (8)$$

where ε^{mag} is the magnetostriction strain.

The back-coupling effects corresponding to magnetostriction strain influencing magnetic field, are considered as negligible.
In a finite element formulation, displacements are approximated in elements as

$$u = N^N u^N \quad (9)$$

where N^N is the array of interpolating functions and u^N the nodal displacement.
The strain can thus be expressed as

$$\varepsilon = D^N u^N \quad (10)$$

where D^N is the spatial derivative of N^N.
The governing equation for the motion of the core subjected to magnetostrictive strain is given by the relationship

$$M\ddot{u}^N + C\dot{u}^N + Ku^N = f^N \quad (11)$$

where M, C and K represent the inertia, damping and stiffness terms, respectively and the term f^N gives the load array containing the forces applied at the nodes. In the present model, the core is excited by the magnetostrictive strains. This yields

$$f^N = \int B^T E \varepsilon^{mag} \, dV \quad (12)$$

The displacement field can be finally obtained from the magnetostrictive strains and, as an example, a frequency sweep at constant induction is presented for a specific core in Fig. 5.

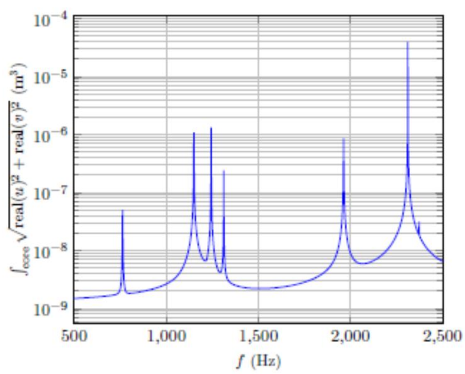

Figure 5. Overall in-plane displacement of the core for a frequency sweep from 500 Hz to 2500 Hz.

The in-plane resonances of the core can clearly be observed in Fig. 5. To obtain a better

understanding of the core motion, a modal analysis is carried out in COMSOL to calculate the core resonances and, as an example, an eigenmode is identified at 2312 Hz, as displayed in Fig. 6.
The resonance at 2312 Hz corresponds to the clear peak displayed in Fig. 5. This resonance is easily excited by the magnetostrictive strains and causes the high vibration amplification at this frequency, as shown in Fig. 5.

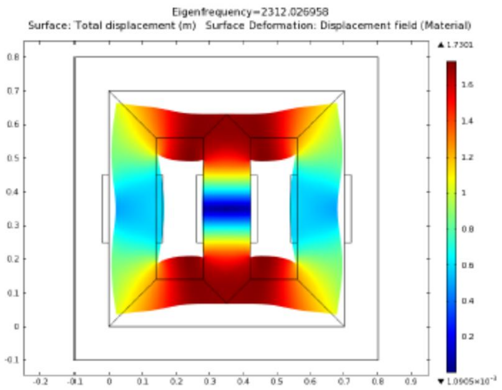

Figure 6. Resonance of the core at 2312 Hz.

4. Acoustic Model

The core motion generates sound waves propagating in a surrounding fluid, such as air or oil, as described by the equation

$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0 \qquad (13)$$

where p is the acoustic pressure and c the speed of sound. The fluid is considered here as non-viscous.
The fluid loading of the windings gives a first boundary condition and is defined as

$$\mathbf{f_p} = -p\mathbf{n} \qquad (14)$$

where p is the fluid pressure and $\mathbf{n}$ a vector normal to the structure surface.
The second boundary condition is given by the particle velocity continuity between structure and fluid, thus yielding

$$v_f = \frac{\partial \mathbf{u}}{\partial t}\cdot\mathbf{n} \qquad (15)$$

where v_f is the particle velocity of the fluid and $\mathbf{u}$ the displacement vector.
The relationship between pressure and velocity is obtained by using the linear equation of motion yielding

$$\rho\frac{\partial \mathbf{u}}{\partial t} = -\nabla p \qquad (16)$$

where ρ gives the fluid density and $\mathbf{u}$ the displacement vector.
For the acoustic analysis, the 2D-model used for the mechanical simulations has to be extruded to a 3D-model. In addition, perfectly matched layers (PML) are implemented to create a free space for sound propagation, as shown in Fig. 7.

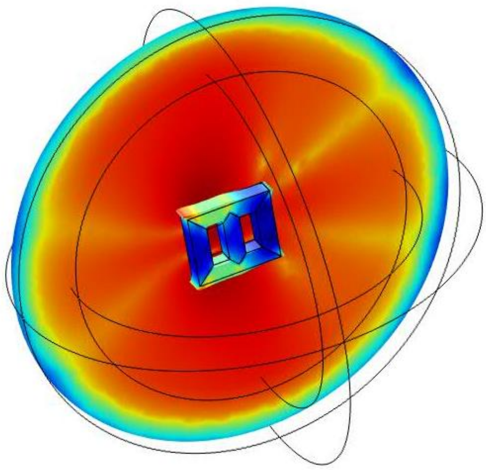

Figure 7. Sound field radiated by the core at a specific frequency.

5. Modeling Procedure Overview

In this section, the procedure to obtain the complete model is described step by step. The two dimensional magnetic flux density is first calculated for the core in time domain. The two dimensional finite element model is implemented and run in the COMSOL AC/DC module. A Fast Fourier Transform is applied to the resulting magnetic flux density in Matlab to obtain the main frequency component at each node. Then, the magnetostrictive strains in rolling and cross rolling directions can be determined at each node from the calculated values of the magnetic flux density by using the magnetostriction tables. The magnetostrictive strains are recalculated to harmonic forces utilized as the driving terms in the equation of motion which is solved in two dimensions by means of the COMSOL Structural Analysis. The resulting vibration field of the 2D-model of the core is extended to a three dimensional representation by using the COMSOL feature designated Extrusion Coupling Variables. By using the COMSOL Acoustics module, the sound pressure and power levels radiated by the vibrating core can be determined accurately when perfectly matched layer (PML) of spherical type are implemented in the model.

6. Prediction Results

The noise radiated in air by a core subjected to three phase excitation is investigated by using simulations and measurements on the test object shown in Fig. 8. Some of the core characteristics are indicated in Table 1.

Table 1. Core characteristics.

Core Height	700 mm
Core Length	700 mm
Limb Pitch	280 mm
Limb Diameter	140 mm
Core Steel Type	0,23 mm Grain-Oriented

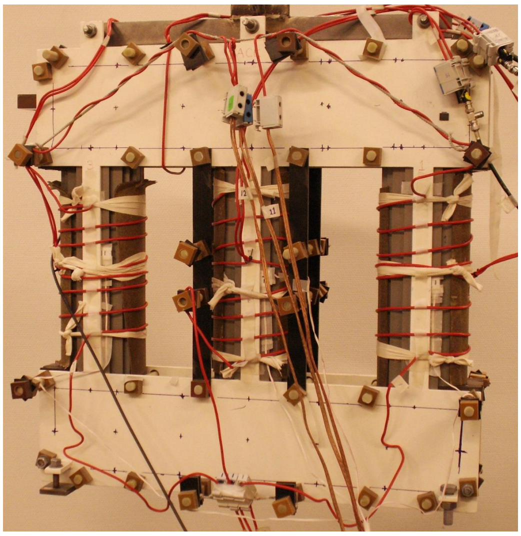

Figure 8. Three phase transformer test core.

A model of this three phase core was created and run in COMSOL according to the procedure described in section 5 to obtain the sound levels radiated in the air surrounding the transformer, as shown in Fig. 9. The sound power level of the core was measured by applying an adapted method based on ISO 3743 and calculated by using the prediction model. The measured and calculated sound power levels obtained from a frequency sweep at constant induction are presented for the test core in Fig. 9. Although the model is rather simple, the predicted results capture the general trend displayed by the measured data without using fitting coefficients.

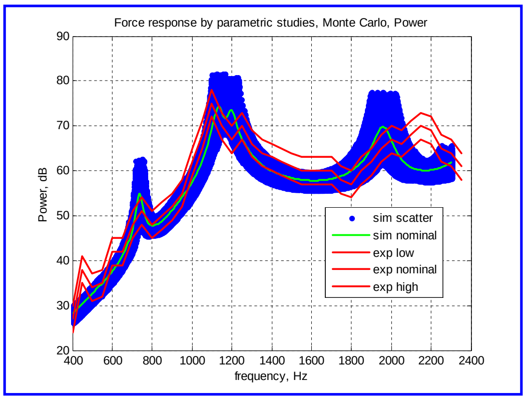

Figure 9. Comparison between measured and predicted sound power levels in dB ref. 1 pW obtained by a frequency sweep from 400 Hz to 2340 Hz.

The plot of the sound power level radiated by the core presents several peaks, as shown in Fig. 9. For example, the peak observed at 760 Hz corresponds to a core resonance which can be determined by calculation in COMSOL, as shown in Fig. 10.

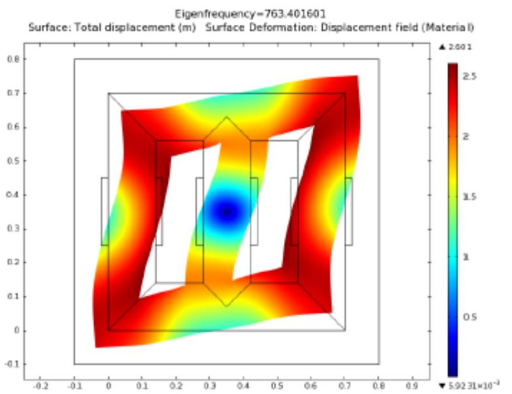

Figure 10. Mode shape of the core predicted in COMSOL at 763 Hz.

As a result, various sensitivity studies can be performed to investigate the impact of material properties and design parameters on the sound levels. Furthermore, it is possible to use the simulation tools for the development and the validation of magnetostriction models.

7. Conclusions

A finite element model to predict transformer core noise was developed by using COMSOL. The electromagnetic model of the core is first solved in the time domain, then the resulting magnetostrictive forces are used in the frequency domain to perform the acoustic analysis. This prediction tool can be used to demonstrate the influence of various material properties and geometrical parameters on the sound power levels of transfomer core noise.

8. References

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