Prediction of Transformer Load Noise

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Abstract: Transformers, as any other industrial products, have to fulfill various requirements on noise levels. Those requirements might be sometimes rather stringent and some other times significantly easier to fulfill. Therefore, it is essential to use appropriate prediction tools in order to select a suitable strategy for noise control.
The paper will focus on the so called load 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 relatively fast and rather accurate tool to perform parametric studies. In the paper, the modeling procedure is described and results from parametric studies are presented.

Keywords: Transformer, windings, acoustics

1. Introduction

Low noise levels are nowadays requested for power transformers in order to comply with customer specifications and environmental legislations [1,2]. Consequently, manufacturers have to improve 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 load noise which constitutes a typical multiphysics phenomenon involving electromagnetism, mechanics and acoustics. The interaction between the alternating currents in the transformer windings and the associated stray field results in varying Lorentz forces generating winding vibrations. The mechanical energy is then transmitted to the tank via the winding clamping system and the insulating oil. The tank acts as a membrane radiating this energy as noise.

Due to the relative 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 power rating are used by most transformer manufacturers [2]. 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. 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 load condition, the transformer windings carry their nominal current. During testing, this is usually achived by short circuiting one winding and feeding the other winding with a 50 Hz or 60 Hz current. The resulting magnetic field **B** induced by the total currents (Amper turns) of both windings is described by using Maxwell's equations. The magnetic field is considered as purely sinusoidal and can be written as

$$\mathbf{B} = \nabla \times \mathbf{A} \qquad (1)$$

where **A** is the magnetic vector potential.
By applying the vector potential formulation, the governing equation for the magnetic field is given by the relationship

$$\nabla \times \frac{1}{\mu} \nabla \times \mathbf{A} = \mathbf{J} - \gamma \frac{\partial \mathbf{A}}{\partial t} + \gamma (\mathbf{v} \times \nabla \times \mathbf{A}) \qquad (2)$$

where μ is the magnetic permeability, **A** the magnetic vector potential, **J** the current density, γ the electrical conductivity and **v** the conductor velocity, which is considered here as negligible.
Due to the relatively high magnetic permeability of the transformer core, the boundary conditions at the core surface are given by

$$\mathbf{n} \times \mathbf{H} = 0 \tag{3}$$

where **n** is the vector normal to the core surface and **H** the magnetic field strength.
The magnetic flux density can be calculated by using a predefined current as the excitation source in the model.

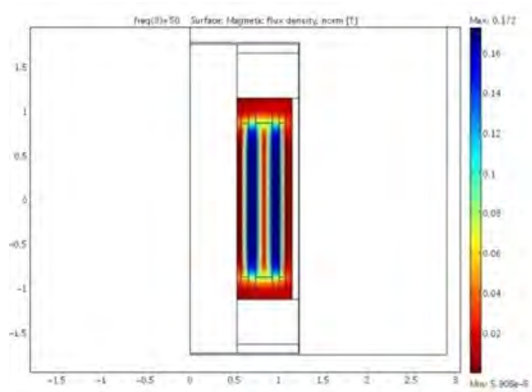

Figure 1. Magnetic flux density inside the winding window.

The Lorentz forces $\mathbf{f}_v$ applied on the windings can be determined from the magnetic field calculations. Those forces are given by the expression

$$\mathbf{f}_v = \mathbf{J} \times \mathbf{B} \tag{4}$$

where **J** is the current density and **B** the magnetic field.
The forces can also be written as a function of the magnetic vector potential **A**

$$\mathbf{f}_\mathbf{v} = \left(-\gamma \frac{\partial \mathrm{A}}{\partial t} - \gamma \nabla \mathrm{V} + \gamma \mathbf{v} \times (\nabla \times \mathrm{A})\right) \times (\nabla \times \mathrm{A}) \tag{5}$$

The Lorentz forces provide the coupling term between the electromagnetic field and the winding motion described by the mechanical model.

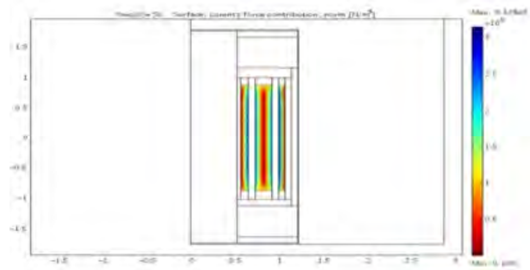

Figure 2. Lorentz forces appearing on windings.

3. Mechanical Model

In the mechanical model, the linear elasticity equations are used to describe the motion of the windings. The equation of motion is given by the expression

$$\nabla \cdot \sigma + \mathbf{f}_\mathbf{v} = \rho \ddot{\mathbf{u}} \tag{6}$$

where σ is the stress tensor, $\mathbf{f}_v$ the volume forces, ρ the density and $\ddot{\mathbf{u}}$ the acceleration vector.
The volume forces $\mathbf{f}_v$ in the equation of motion represent the Lorentz forces applied on the windings.
The stress tensor σ is a function of the strain tensor ε as given in Hooke's law

$$\sigma_{ij} = c_{ijkl}\varepsilon_{kl} \tag{7}$$

where c_{ijkl} is the stiffness tensor and ε_{kl} the strain tensor.
The strain tensor ε is a function of the displacement

$$\varepsilon = \frac{1}{2}[\nabla \mathbf{u} + (\nabla \mathbf{u})^T] \tag{8}$$

where **u** is the displacement vector.
The rather complex structure of the winding is simplified to an equivalent cylinder presenting orthotropic properties. In addition, the rotational symmetry of the winding is used to provide a three dimensional axisymmetric model. The governing equations have thus to be written for the two dimensional axisymmetric model in cylindrical coordinates. The relationship between strain and displacement in the two dimensional axisymmetric case is given by

$$\varepsilon_r = \frac{\partial u_r}{\partial r}, \varepsilon_\theta = \frac{u_r}{r}, \varepsilon_z = \frac{\partial u_z}{\partial z}, \varepsilon_{rz} = \frac{1}{2}\left(\frac{\partial u_r}{\partial z} + \frac{\partial u_z}{\partial r}\right), u_\theta = 0, \varepsilon_{r\theta} = \varepsilon_{z\theta} = 0 \tag{9}$$

There is no displacement and no shear strain in the circumferential direction.
By combining the previous equations, a relationship in cylindrical coordinates is obtained for the equation of motion

$$-\mathbf{S}_1^T[C]\mathbf{S}_2 u = \mathbf{f}_\mathbf{v} \tag{10}$$

where $\mathbf{S}_1$ and $\mathbf{S}_2$ are two operators defined as

$$\mathbf{S}_1 = \begin{pmatrix} \frac{\partial}{\partial r} + \frac{1}{r} & 0 \\ 0 & \frac{\partial}{\partial z} \\ -\frac{1}{r} & 0 \\ \frac{\partial}{\partial z} & \frac{\partial}{\partial r} + \frac{1}{r} \end{pmatrix} \quad \mathbf{S}_2 = \begin{pmatrix} \frac{\partial}{\partial r} & 0 \\ 0 & \frac{\partial}{\partial z} \\ \frac{1}{r} & 0 \\ \frac{\partial}{\partial z} & \frac{\partial}{\partial r} \end{pmatrix} \tag{11}$$

and $[C]$ is the stiffness tensor of an orthotropic material [5].
By introducing the volume forces in the equation of motion, the displacement of the orthotropic windings can be determined at first for the axisymmetric conditions without the oil loading.

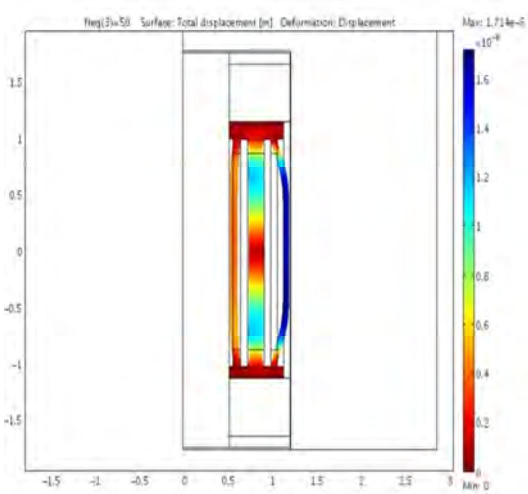

Figure 3. Motion of windings subjected to Lorentz forces.

4. Acoustic Model

The displacement of the windings generates sound waves in the surrounding oil which in turn implies a surface pressure on the structure. Sound waves propagating in fluid, such as oil and air, are described by the equation

$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0 \tag{12}$$

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

$$\mathrm{f}_\mathbf{p} = -p\mathbf{n} \tag{13}$$

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

$$v_f = \frac{\partial \mathbf{u}}{\partial t}\cdot\mathbf{n} \tag{14}$$

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

$$\rho\frac{\partial \mathbf{u}}{\partial t} = -\nabla p \tag{15}$$

where ρ is the fluid density and $\mathbf{u}$ the displacement vector.

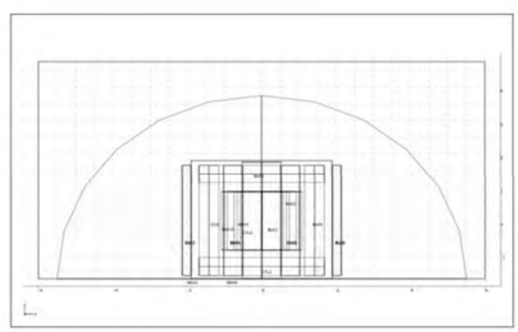

Figure 4. Drawing of the transformer model.

5. Modeling Procedure Overview

In this section, the procedure to obtain the complete model is described step by step. The two dimensional magnetic field is first calculated for the windings around the core limb. The associated Lorentz forces applied on the windings can then be determined from the currents and the resulting stray fields. The two dimensional finite element model is implemented and run in the COMSOL AC/DC module. The harmonic forces can be utilized as the driving term in the equation of motion which is solved for oil loaded windings in two dimensions by means of the COMSOL Structural Analysis and Acoustics modules. The resulting vibration field is extended to a three dimensional representation by using the COMSOL feature designated Extrusion Coupling Variables. The field is then mapped onto a three dimensional model of the transformer core, tank and environment. If a three-phase transformer is investigated, a 120 degree phase shift between the three windings can be implemented in the model. By using the COMSOL Acoustics module, the sound transmission paths such as insulating oil, tank walls and air surrounding the transformer are modeled by finite elements and the sound pressure levels can be determined at any positions in oil or air.

6. Prediction Results

The load noise of a single phase transformer is investigated. Some of the transformer characteristics are indicated in Table 1.

Table 1. Transformer characteristics.

Power Rating	145 MVA
Tank Length	3,8 m
Tank Width	2,7 m
Tank Height	3,5 m

A model of this single phase transformer was created and run in COMSOL according to the procedure described in section 5 to obtain the sound levels emitted in the air surrounding the transformer, as shown in Fig. 5.
The sound power level of the transformer was measured according to the applicable IEC standard [2] and was calculated by using the prediction model. The deviation between measured and calculated sound power levels was found to be less than 2 dB. This can be considered as an acceptable match between experimental and predicted results.

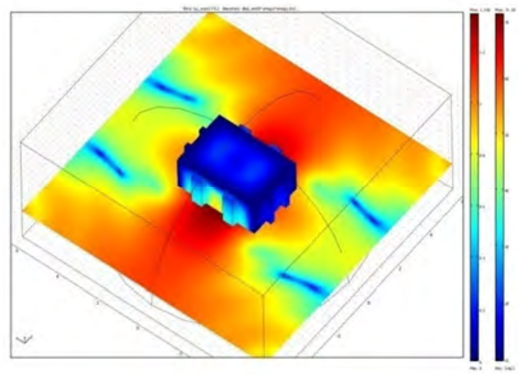

Figure 5. Tank wall displacement and sound pressure field outside the tank.

Sensitivity studies have been performed to investigate the effects of some material properties and design parameters on the sound levels.
For example, it was found that tank thickness variations of 1 mm can imply sound power level differences of nearly 5 dB. This rather large discrepancy in sound power can be attributed to the impact of the tank eigenfrequencies on sound transmission.
Furthermore, changes of 20% in the Young's modulus of the radial spacers in the windings result in sound power level differences of approximately 1,5 dB.
The simulations also reveal that the sound power level varies with more than 1 dB if the Young's modulus of insulation paper in the windings is altered by 20%.
The parametric studies clearly show the complex interactions of the design parameters and the effects of the material properties on the sound power levels. The sensitivity tests also underline the need of reliable input data to ensure accurate predictions. In particular, the dynamic properties of non-linear materials shall be properly determined by means of experimental methods.

7. Conclusions

A finite element model to predict transformer load-noise was developed by using COMSOL. This prediction tool can be used to demonstrate the influence of various material properties and geometrical parameters on the sound power levels.

8. References

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