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Executive Summary of the Thesis

Vibroacoustic methodology for transformers noise computation based on FEM multiphysics approach

Laurea Magistrale in Aeronautical Engineering - Ingegneria Aeronautica

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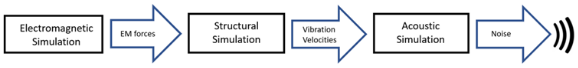
1. Introduction

The objective of this work is to build a methodology based on Finite Element Method for computing noise emissions of transformers based on a review of the numerous papers present in literature as well as on what has been studied by researchers in the company during the past years. The main source mechanisms are studied and modeling techniques are proposed. Since some of the mechanisms involved in transformers noise are not perfectly understood still today, this work gives also a contribution to the research.

Based on the nature of the problem, a multiphysic approach is adopted. The three involved physics, Electromagnetism, Structural Mechanics and Acoustics (air-borne noise) are explicitly modeled making use of FEM and one-way coupling. Figure 1 shows the workflow followed in the methodology.

Figure 1: Methodology workflow



In the past years, a technology gap between research and engineering was suffered on acoustic topics related to transformers in Hitachi Energy. Many independent studies have been conducted by researchers but none of them has been converted in a ready-to-use methodology to be integrated in the engineering process. However, with the new eco-directives coming and the pressing demand from customers, a methodology for noise emission computation became a must.

2. Transformers noise

The main noise sources can be listed in Lorentz, Maxwell and magnetostrictive forces. [1]

Lorentz forces are generated by the interaction between the current flowing in the winding and the induced magnetic field. Lorentz forces depend on the square of the current, meaning that their frequency is double the current one. The emitted noise is the so-called Load Noise [2] and its power depends on the fourth power of the input current. $\mathbf{A}$ is the magnetic potential vector, $\mathbf{J}$ is the current density, $\mathbf{B}$ is the magnetic flux density, μ is the magnetic permeability, σ is electric conductivity, $\mathbf{F}$ is the volumetric density of Lorentz forces.

$$\nabla \times (\frac{1}{\mu}\nabla \times \mathbf{A}) + \sigma\frac{\partial \mathbf{A}}{\partial t} = \mathbf{J}$$

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

$$\mathbf{F} = \mathbf{J} \times \mathbf{B}$$

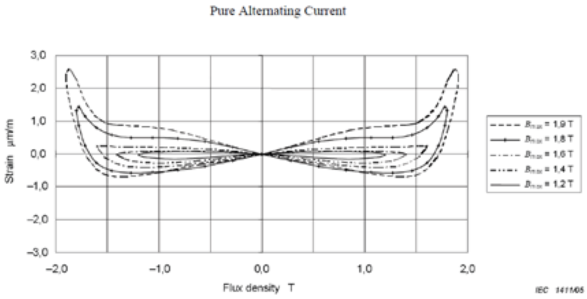
Maxwell forces, also known as magnetic forces, are surface forces concentrated on the free surfaces of the core. They can be described as a state of stress acting on the free surfaces of the core depending on the square of the magnetic field, from which volumetric forces can be derived. For this reason, they have double the frequency of the input current. The sound power generated by Maxwell forces depend on the fourth power of the current.

$$S = \frac{1}{\mu}\begin{bmatrix} B_x^2 - B^2/2 & B_xB_y & B_xB_z \\ B_xB_y & B_y^2 - B^2/2 & B_yB_z \\ B_xB_z & B_yB_z & B_z^2 - B^2/2 \end{bmatrix}$$

$$\mathbf{f}^V_\alpha = \frac{\partial}{\partial x_\beta} S_{\alpha\beta}$$

Magnetostriction is a magneto-mechanical coupling typical of ferromagnetic materials, as the laminas used to compose the core. When a magnetic flux density travels in such materials, a mechanical deformation occurs, generating vibrations and consequently noise [4]. Magnetostriction is described by non-linear hysteretic curves linking deformation to magnetic field, known as butterfly curves due their shape. Figure 2 shows an example. It is measured using the so-called Epstein frame by means of strain gauges, piezoelectric accelerometers or vibrometers.

Figure 2: Butterfly curves [5]



Analitically, magnetostrictive deformation λ depends on the magnetic field strength H by a polynomial in which only even powers are present. Thus, magnetostriction has a fundamental harmonic at double the frequency of magnetic field plus higher even harmonics. It is in general transversely anisotropic due to the cold rolling technique used to realized core laminas. Finally, it depends on applied stress, with compressive stresses leading to increasing magnetostriction. x denotes the rolling direction, y and z the transverse ones, A is the derivative matrix which links element deformation to nodal displacement in the context of Finite Element approximation, C is the elasticity tensor.

$$\lambda_x = \sum_i \alpha_i H_x^{2i} + \beta_i H_y^{2i} + \gamma_i H_z^{2i}$$

$$\lambda_y = \lambda_y = \sum_i \phi_i H_x^{2i} + \omega_i H_y^{2i} + \epsilon_i H_z^{2i}$$

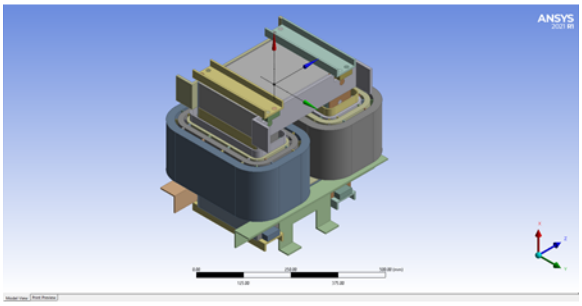
$$\mathbf{f}^V_{ms} = \int A^T C \boldsymbol{\lambda} dV$$

Noise generated by magnetostriction and Maxwell forces is referred to as Core noise.

3. Methodology description

Simulations are performed using Ansys. Electromagnetic dynamic forces are computed in Ansys Maxwell. The forces are mapped onto the structural model representing the structural excitation and vibration velocities are computed. The velocities are mapped onto the acoustic model representing the acoustic excitation and acoustic far-field quantities are finally computed. One-way coupling is assumed. A traction reactor, shown in Figure 3, is modeled to test the methodology. The winding is modeled as homogenized and the core as a monolithic solid (not laminated as in reality), after having proved through dedicated models that these are acceptable approximations.

Figure 3: Developed model



3.1. Electromagnetic model

After having defeatured the geometry, the latter is imported in two different Maxwell simulations, from which winding and core forces are computed respectively. An enclosure representing the surrounding air is modeled as well.

The following hypotheses are assumed for Lorentz forces computation, and for this reason, they are computed through a harmonic analysis:

- Linearity
- Isotropic material
- Harmonic excitation
- Steady-State

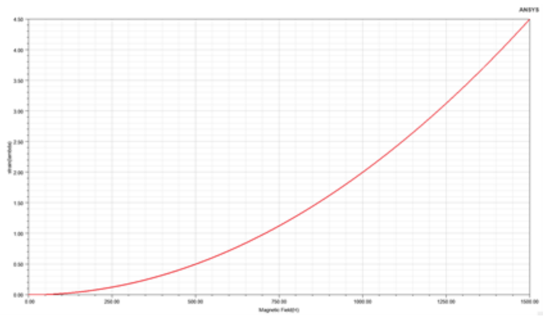
The following hypotheses are assumed for core forces computation and for this reason, they are computed through a transient analysis:

- Constant magnetic permeability
- Isochoric, non-hysteretic magnetostriction
- No dependance of magnetostriction on stress
- Isotropic material
- Harmonic excitation

The minimum time step is calculated according to Shannon theorem based on the maximum expected force frequency. A complete current period is simulated.

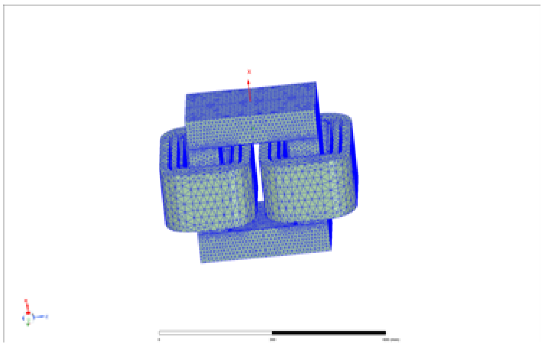
Material properties are copied from suppliers datasheets. A quadratic relation between magnetostrictive deformation and magnetic field is assumed, as shown in Figure 4, which is a good approximation for low inductions [4].

Figure 4: Implemented magnetostriction curve



Concerning the mesh, Ansys Maxwell allows to use tetrahedral elements only and performs an automatic refinement when a harmonic simulation is performed. The auto-refined mesh, shown in Figure 5, is then used as the mesh of the transient analysis, leading to higher accuracy. This is the reason why two different electromagnetic analyses are performed.

Figure 5: Refined electromagnetic mesh.



A current intensity excitation is assigned. Only an harmonic at 50 Hz is here assumed.

A non-reflecting boundary condition is assigned to the external surfaces of the enclosure, while symmetry boundary conditions are defined to exploit 1/8th symmetry.

As a first check, magnetic flux density B is computed using an analytical model and then compared with the computed one, verifying that the results are in accordance.

As a second check, the FFT of the forces is computed. Under the hypoteses assumed, the electromagnetic forces are expected to have a DC component plus an AC component at double the current frequency, i.e. at 100 Hz.

Figure 6: Core forces FFT

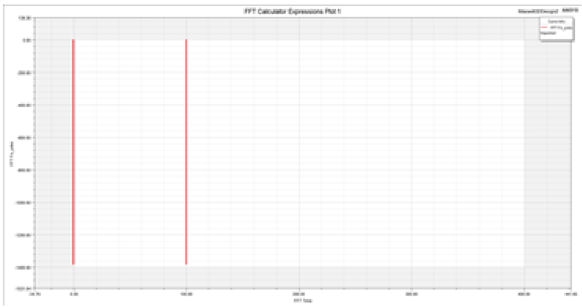
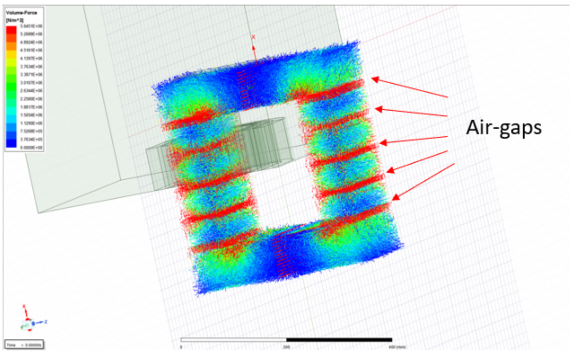


Figure 7 shows the distribution of Core forces. Maxwell and magnetostriction forces are concentrated at the air-gaps due to material discontinuity, which leads to high gradient of the magnetic field and consequently to the intensification of Maxwell and magnetostriction forces.

Figure 7: Core forces



3.2. Structural model

In this section the structural model used to compute the vibration velocities of the structure will be presented.

The same winding and core geometry of the electromagnetic analyses must be used for performing the structural analysis, due to a topology-based force interpolation.

The following hypotheses are assumed and for this reason a harmonic analysis is performed:

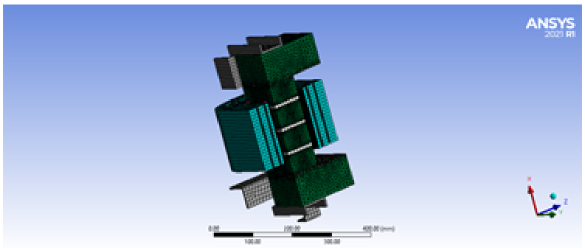
- Linearity
- Harmonic excitation
- Steady-State
- Deformation due to DC forces neglected
- Temperature is supposed equal to 22 °C

Core forces are computed through a transient electromagnetic analysis. An FFT of the core forces is performed by Ansys and the computed spectrum is given in input as the excitation of the structural model. Since only the current harmonic at 50 Hz has been considered in the electromagnetic simulation and since the electromagnetic forces have double the frequency of the current, the analysis is run at 100 Hz only.

Materials are assigned according to datasheets provided by suppliers. Winding is in general composed by several materials (conductor, insulation, protections). Since it has been homogenized, equivalent properties are calculated through a specific technique based on beam model.

Hexahedral quadratic mesh is assigned to all the parts, apart from the core. A transitioning tetrahedral mesh, refined close to the air gaps (where forces are concentrated) and coarser far from them has been proven to be the best choice for core meshing in terms of interpolation quality and solution accuracy. Figure 8 shows the structural mesh.

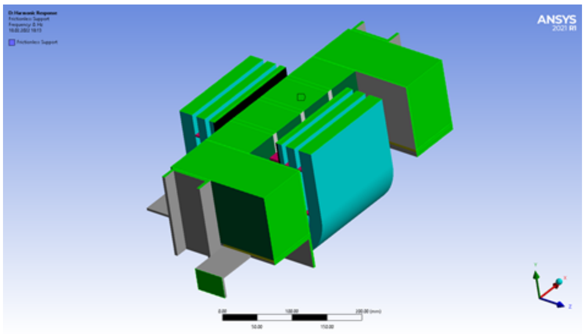
Figure 8: Structural mesh



Nodal volumetric forces are mapped into the structural model. After having imported the loads, the quality of the interpolation is checked.

The structural model is constrained to avoid rigid body motions without impeding the exploitation of the operative deformations. In this case, the two symmetries with respect to XY and XZ planes are exploited and rigid motion in the X direction is constrained imposing a null displacement of the lower clamping profile surface parallel to the YZ plane, as shown on Figure 9.

Figure 9: Structural BCs

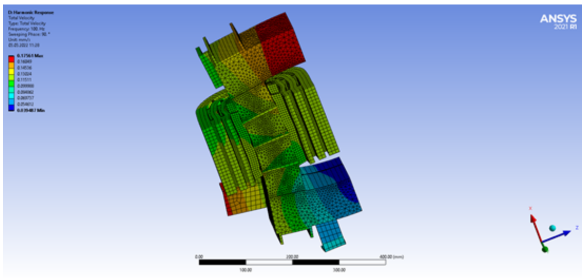


All the parts have been bonded together. This has been proven to be an acceptable choice through a non-linear quasi static analysis in which the clamping of the core is simulated, computing the final contact status.

Figure 10 shows the operative deformation. A maximum vibration velocity of 0.176 mm/s is computed. Equivalent Radiated Power (ERP) in x (vertical) direction is predominant since core forces are mainly directed in x direction. ρ is the air density, c is the speed of sound, A is the area of the radiating surface and $< v_n^2 >$ is the surface averaged mean square normal velocity.

$$ERP = \rho c A < v_n^2 >$$

Figure 10: Deformed shape and velocity contour



3.3. Acoustic model

In this section, the model used to compute the acoustic response of the structure is presented.

The external fluid domain must be modeled. A box enclosing the structure is modeled and the structure geometry is subtracted from the same box. The structure is not modeled due to the hypotheses of no fluid-structure interaction, which is appliable in this case. Several sensitivity studies based on Monopole and Dipole models have been performed to understand how to model the acoustic domain. An acoustic domain with a box shape and the usage of PML elements has been proven to be the best solution in terms of accuracy and convergence. PML elements provide absorption of the acoustic wave representing the infinity. [6][7]

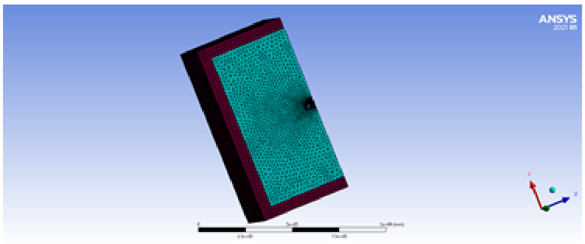
The following hypotheses for the acoustic analysis are assumed and for this reason, a harmonic acoustic analysis is performed:

- Linearity
- Harmonic excitation
- No fluid-structure interaction
- Compressible and non-viscous fluid
- Irrotational flow
- Adiabatic and reversible pressure change
- Steady-State

The material assigned to the enclosure and the PML region is air. Reference pressure is set equal to 2e-11 MPa, which correspond to the minimum audible pressure variation. This quantity is used as the reference pressure to compute sound pressure level in dB scale.

The finite elements used in acoustics when fluid-structure interaction is neglected, as in this case, have 1 degree of freedom only per node, i.e. acoustic pressure. Tetrahedral quadratic elements have been proven to be acceptable in terms of accuracy and ease of meshing. Meshing with hexahedral elements is difficult and leads to high element distortion. The element size should not be greater than 1/4th of the shortest acoustic wavelength. Conformal mesh must be used to avoid reflections. Finally, care must be taken to the meshing of the exciting surfaces, since it influences the quality of the interpolation. Figure 11 shows the acoustic mesh.

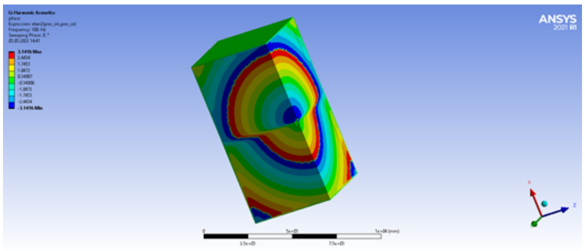
Figure 11: Acoustic mesh



The excitation is provided by the vibration velocities of the transformer surfaces, mapped from the harmonic structural analysis. Quality of the interpolation can be checked. PML region must be defined explicitly selecting which region has to be meshed with such elements. A Dirichlet boundary condition p=0 is automatically imposed on the PML external surface. Finally, symmetries are defined on the faces lying on symmetry planes.

As a first check, pressure phase is computed. It should be smooth in the whole domain approaching a spherical shape far from the source, as expected for waves emitted by 3D objects. Figure 12 shows the computed phase contour.

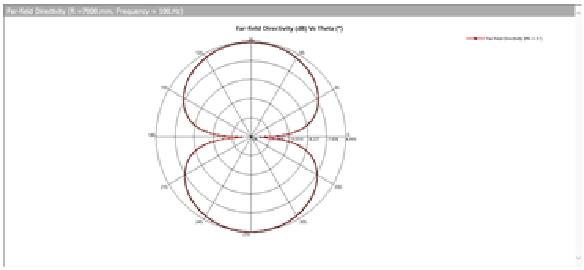
Figure 12: Pressure phase contour



A second check is that of plotting the Sound Pressure Level along some arbitrary paths. Keeping two points on this path far enough from the source but still inside the enclosure (not in the PML region) and one at double the distance of the other one, a difference of 6 dB should be theoretically observed.

Far-field quantities can be computed in an arbitrary point outside the modeled acoustic domain making use of the Equivalent Source Method [6]. Figure 13 shows the directivity plot on a circular path enclosing the source on the XZ plane.

Figure 13: Directivity plot



Finally, the Sound Power Level is output and radiation efficiency is calculated. Computed Sound Power Level and total ERP are equal to 35.9 dB and 56.8 dB respectively. A relatively low radiation efficiency σ=0.0082 (ratio between Sound and Radiated Power) is calculated. This is due to the low excitation frequency (100 Hz), which is far from the coincidence frequencies of the core and the winding.

$$\sigma = \frac{W}{ERP}$$

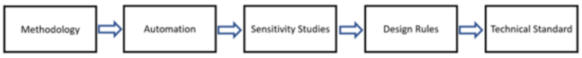
4. Conclusions

The present work proposes a methodology for computing acoustic emissions of a dry-type transformer based on a Multi-physics Finite Element procedure. The proposed workflow demonstrates the capability of such procedure of obtaining all the interesting acoustic quantities which can be also measured by experimental tests. Experimental tests will be run on the analyzed model in the coming months.

Further developments will aim to the relaxation of the strongest assumptions. Also, others transformers designs will be object of study.

The methodology represents the first step of a roadmap which will take to the redaction of a technical standard containing design rules for noise minimization. The bridge is represented by the building of an automation (Ansys Shell) through which sensitivity analyses on different transformers will be run and design rules will be derived. Figure 14 shows a schematic of the roadmap.

Figure 14: Directivity plot



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