Journal of Energy

VOLUME 68 Number 4 | 2019 | Special Issue

journal homepage: http://journalofenergy.com/

Numerical Computation of the Vibroacoustic Behaviour of an Oil-Immersed Power Transformer

Bruno Bosnjak, Dariusz Nowak, Sever Michalowski
Hyundai Electric Switzerland AG, Zürich, Switzerland
E-mail: bruno.bosnjak@hyundai-electric.ch

***Abstract*— This paper presents a numerical calculation method that allows for the simulation of the mechanical and acoustic behaviour of a transformer tank. In order to simulate the vibroacoustic behaviour of an oil-immersed power transformer, an acoustic-mechanical coupled three-dimensional finite-element method model of a transformer was setup. The simulation is performed in the frequency domain at frequencies adjacent to the driving frequency. A vibration source closely resembling the actual active part of the transformer is placed within the oil-filled tank that mechanically represents an acoustic cavity with flexible steel boundaries. Via a fluid-structure interface the vibration source generates acoustic waves in the oil medium which partly transmit through the tank wall structure and partly reflect within the steel transformer tank again via a fluid-structure interface. The vibrating tank is then coupled with the external acoustic air medium and the corresponding sound field is calculated and evaluated according to IEC 60076-10. This numerical computation allows for the direct calculation of the complete vibrational and acoustic behaviour of a transformer.**

***Index Terms*— Power Transformer Noise, Finite Element Method, Multiphysics, Vibration, Tank**

I. INTRODUCTION

The noise emitted by power transformers is generally unpleasant for nearby residents and increasing urbanization go hand in hand with the increasing energy needs of the population. In order to protect the general population from adverse effects of continuous exposure to noise, the local and national legislations in the developed countries limit the amount of noise emitted into the environment by power transformers (such as [1]). Therefore, it is important to accurately calculate and predict the noise emitted by a transformer in operation on order to satisfy the customer requirements and to stay within the legislative limits. This paper focuses on the numerical analysis of the vibroacoustic behavior of a power transformer in operation, namely during a short circuit test with 100% of nominal current flowing through the transformer windings. Coupled numerical simulations provide a powerful tool for the optimization of the tank during transformer design phase with respect to low noise emissions.

II. TRANSFORMER NOISE

Power transformers are a source of low frequency tonal noise during operation. Power transformer noise can be divided into three components according to the point of origin and noise generation mechanism – core noise (no load noise), winding noise (load noise) and cooling system noise.

The core noise is, to a great degree, caused by magnetostrictive core vibrations originating from oscillatory magnetic fields in the core. Maxwell force acting between the electrical steel sheets of the core also contribute to the noise generation, albeit to a smaller degree than magnetostriction. Since magnetostriction acts unidirectionally, the generated core noise has tonal components at twice the line frequency and at even higher harmonics thereof.

Winding noise is generated by winding vibrations caused by Lorentz forces acting on the transformer windings in load conditions. Due to the imperfect magnetic coupling of the windings, a stray magnetic flux is generated between the transformer windings. The interaction of the stray magnetic flux and the current-carrying conductors of the windings leads to the generation of Lorentz forces that also act unidirectionally generating noise at twice the line frequency.

Fans and pumps of the transformer cooling system generate a broadband noise typical for forced flow of air or oil. Usually, the cooling system noise is lowered by reducing the speed of the fans and therefore reducing the air flow. Reduced air flow in the fans lowers the cooling performance of the system and increases the number of fans necessary to achieve the required cooling performance [2].

The total sound power level of a transformer at certain load conditions is given by the logarithmic sum of these three sound power components at defined load conditions [3].

Bruno Bošnjak, Dariusz Nowak, Sever Michalowski, Numerical Computation of the Vibroacoustic Behaviour of an Oil-Immersed Power Transformer, Journal of Energy, vol. 68 Number 4, Special Issue (2019), p. 3–7
https://doi.org/10.37798/2019684208

III. GOVERNING EQUATIONS

Numerical calculations of the vibroacoustic behavior of an oil immersed power transformer must consider the interaction between the magnetic, mechanical and acoustic physical domain. Since the focus of this paper is on the vibroacoustic properties of the transformer tank, the magnetic domain is omitted from this consideration. The vibrations caused by the magnetostriction, Maxwell forces and Lorentz forces are directly measured on an actual transformer unit and set as the initial conditions in the vibroacoustic simulation.

For the mechanical field in the solid, the materials used are considered to have linear elastic and isotropic properties. Therefore, their dynamic behavior can be described using the following partial differential equation[4]:

$$\frac{E}{2(1-\nu)}\left((\nabla\cdot\nabla)\vec{d}+\frac{1}{1-2\nu}\nabla\left(\nabla\cdot\vec{d}\right)\right)+\overrightarrow{f_V}=\rho\frac{\partial^2\vec{d}}{\partial t^2} \tag{1}$$

where E is the modulus of elasticity, ν is the Poisson's ratio, ρ is the material density, f_v is the volumetric force and d is the mechanical displacement. As for the acoustic wave, assuming a homogenous, non-viscous fluid, its' propagation is governed by the linear wave equation[5]:

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

where p is the acoustic pressure and c sound velocity in the fluid. The acoustic pressure can be calculated using the scalar velocity potential ψ as follows:

$$p=\rho\frac{\partial\psi}{\partial t}. \tag{3}$$

These two domains are then coupled at the fluid-structure interface, where the condition that the normal component of particle velocity $\partial\psi/\ \partial n$ in the fluid must be equal to the normal component of the surface velocity v_n of the solid at the fluid-structure interface. Therefore, the following condition must be satisfied at the fluid-structure interface in order for the two domains to interact:

$$v_n=\vec{n}\cdot\left(\frac{\partial\vec{d}}{\partial t}\right)=-\vec{n}\cdot\nabla\psi=-\frac{\partial\psi}{\partial n} \tag{3}$$

IV. MEASUREMENT ON A 18MVA TRANSFORMER

The vibrations of the tank and the active part of a three phase 18MVA transformer were measured during operation. All measurements were performed using a laser Doppler vibrometer. The measurement equipment allows only for measurement of the vibration in the plane directly perpendicular to the laser beam. Strictly speaking, the laser beam impinges on the surface of the object at angle slightly different than 90º. Therefore, the normal of the local surface and the direction of the laser beam are not parallel. This introduces a certain amount of error to the measurement which is typically negligible with the increasing distance from the measured object due to the reduction of the parallax angle. The distribution of the measurement points on the active part of the transformer can be seen in Figure 1.

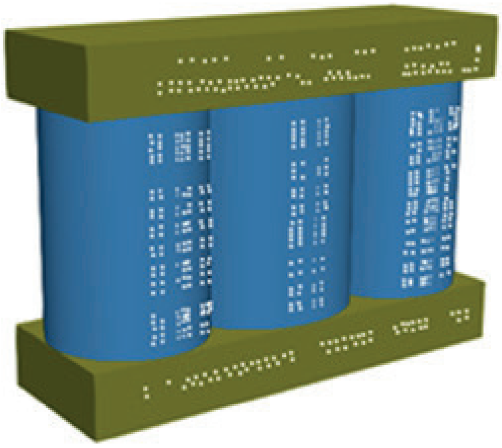

Figure 1 Distribution of measurement points on the active part

The measured displacements and velocities in the measured positions were used as basis for the calculation of the actual vibrations of the active part immersed in oil.

The measurement of the tank vibrations was performed during a short-circuit test load condition with the 100% of the load current in the windings. The scanning point were uniformly distributed on the transformer tank plates as shown in Figure 2.

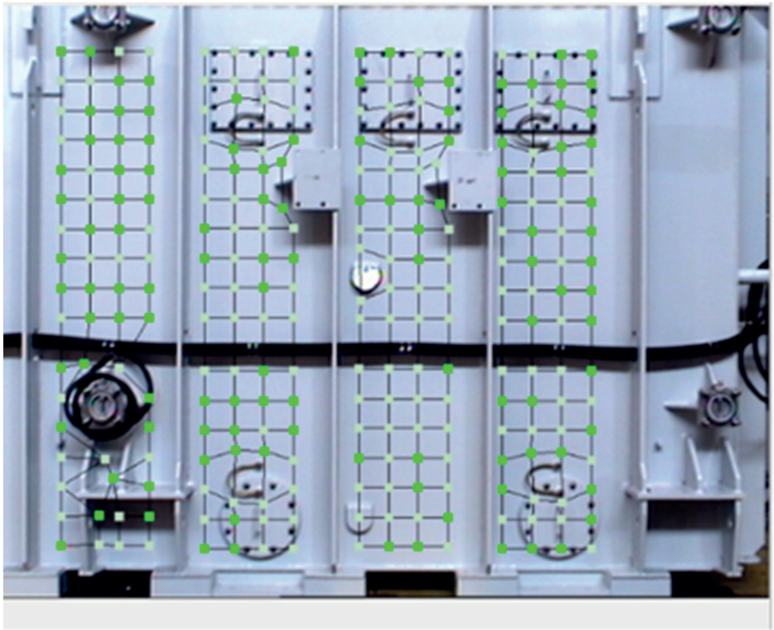

Figure 2 Distribution of the scanning points on the transformer tank

Certain areas of the tank had to be omitted from the measurement since they were covered in cables, pipes, flanges and other equipment and supporting structures present on the tank wall which are necessary for the functioning of the transformer. Figure 3 shows the actual measurement setup during the measurement procedure.

Figure 3 Measurement of the vibration of the transformer tank

V. NUMERICAL VIBROACOUSTIC MODEL OF A TRANSFORMER

Using the measured vibrations of the active part of the transformer, actual vibrations of the active part immersed in oil (as opposed to the active part in air) are calculated using a simplified 3D coupled model of the active part of transformer. The calculated displacements of the oil-immersed active part are then taken as the mechanical excitation in a 3D finite-element coupled acoustic-mechanic model of the transformer active part, oil, tank and the surrounding air. The phase separation of the each of the three limbs in considered by separating them in phase by 120º. The fluid-structure interfaces between the two domains (core – oil – tank wall – air) allow for the interaction of two domains and the transmission of incident vibration in the mechanical domain and sound pressure in the acoustical domain. Boundary condition in the acoustic domain is a perfectly matched layer (PML) of elements which employs additive dissipative terms in each element of the layer that attenuate outgoing waves exponentially, therefore effectively providing free field conditions at the boundary [6][7]. A slice of the 3D FEM model is shown in Figure 4.

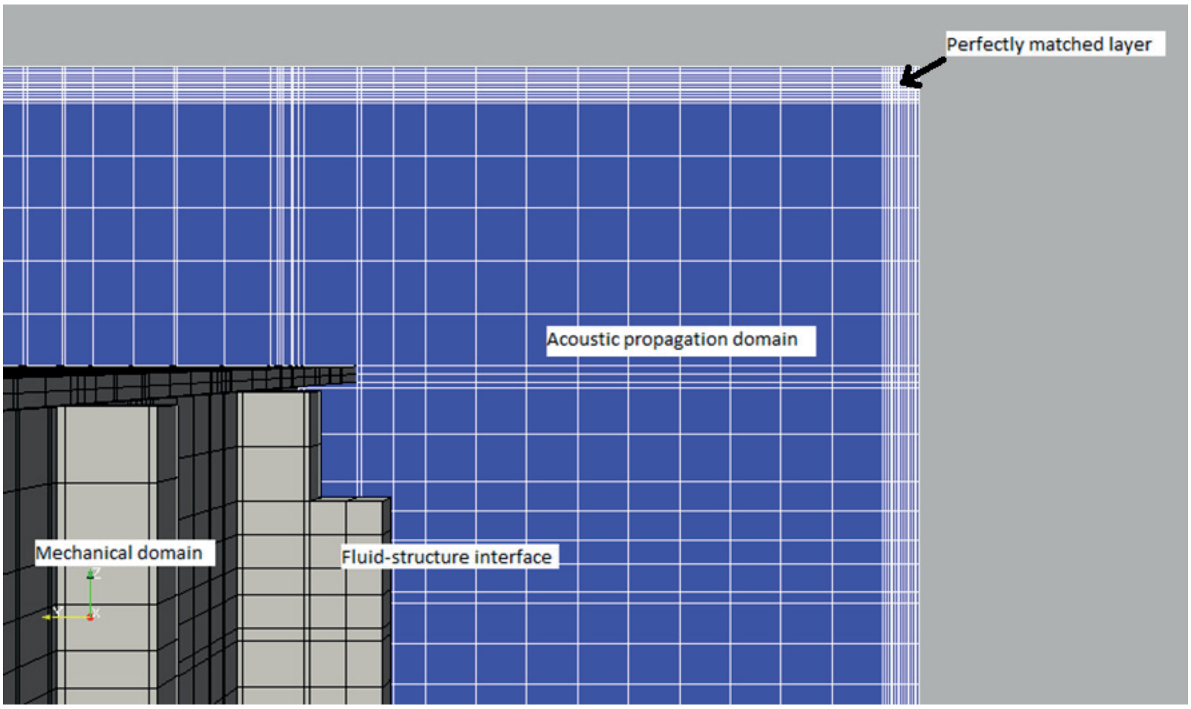

Figure 4 Slice of the vibroacoutic 3D FEM model

The simulation uses a direct solver where both the acoustical and the mechanical domain are solved simultaneously, within one matrix [7]. The surrounding floor is acoustically modeled as perfectly reflecting. The complete domain is discretized using a structured mesh in order to ensure high quality element shapes needed to avoid artificial numerical stiffening which might stem from inadequate mesh quality [7]. Since we are observing a transformer in short-circuit conditions where, for 50Hz transformers, the dominant vibration source is the 100Hz component, the frequency domain simulation is performed only for this 100Hz frequency. The finite-element model consisted of approximately 1,200,000 three dimensional finite elements.

VI. SIMULATION RESULTS

Performing the calculation, we can obtain the complete vibroacoustic behavior of the transformer tank. This includes the mechanical and acoustic interaction inside the tank, on the tank and in the surrounding air. The measured velocities of the tank vibration acquired using a 3D scanning Doppler vibrometer can be seen in Figure 5. The corresponding simulation of the vibration of the transformer tank plates can be seen in Figure **6**.

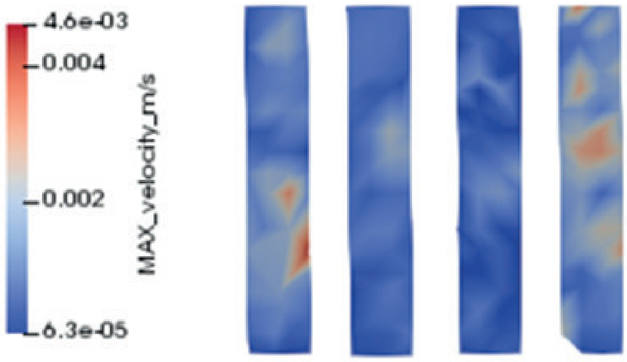

Figure 5 Measured vibration of the tank plates acc. to Figure 2

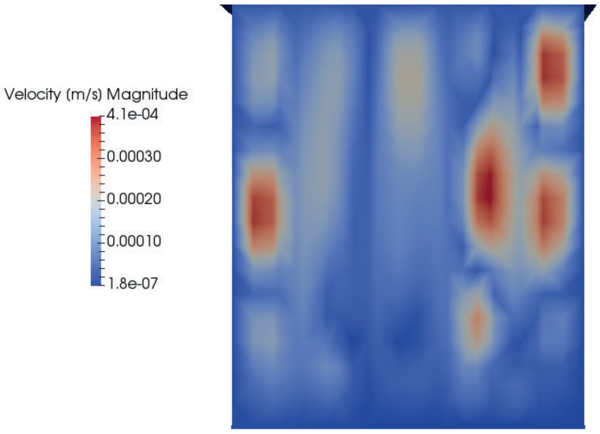

Figure 6 Simulated vibration of the tank plates at 100Hz

Comparing the two vibration forms, there are similarities in the distribution and the magnitude of the two vibration forms. The measured and simulated tank accelerations are similar, even though the exact operational deflectional shape modes do not correspond precisely. This is due to a multitude of factors influencing the vibrational behavior and the measurement such as the mechanical connection of the tank to ground, influence of the measurement setup and temperature as described in [8].

VII. CONCLUSION

The vibroacoustic behaviour of the transformer tank that was simulated generally follows the vibration form measured using a laser Doppler vibrometer and it can be sufficiently sophisticated to show general trends and vibrational tendencies of a particular transformer tank. The phase relationships in the simulated model broadly correspond to the measured ones. The scope of these investigations is generally limited to qualitative analysis since the actual amplitude of the vibration varies with other parameters that influence the vibration with influence the noise which cannot be completely described within a model or are not practically feasible to be calculated in a reasonable amount of time. Advancing these types of simulations by implementing them in the time domain does not seems feasible since a steady-state solution within a simulation is extremely time-consuming to achieve with the current state of art. Nonetheless, this simulation allows for an in-depth analysis of the interactions of the active part, oil and the tank. This allows for the optimization of the vibrational behaviour of a transformer tank by implementing mechanical changes with the general aim of reducing vibration of tank and consequently the noise emitted by the transformer.

VIII. REFERENCES

[1] Gesetz zum Schutz vor schädlichen Umwelteinwirkungen durch Luftverunreinigungen, Geräusche, Erschütterungen und ähnliche Vorgänge (Bundes-Immissionsschutzgesetz - BImSchG)

[2] T. Stirl, J. Harthun, F. Hofmann "New Trends in Noise Reduction of Power Transformers", CIRED 21st International conference on Electricity Distribution, Frankfurt 2011, Paper 0086

[3] International Standard IEC 60076-10:2016 Power Transformers – Part 10: Determination of sound levels

[4] F. Ziegler, 1991, *Mechanics of Solids and Fluids*, Springer-Verlag, Vienna

[5] G. S. Kino, 1987, *Acoustic Waves: Devices, Imaging, and Analog Signal Processing*, Prentice-Hall, Englewood Cliffs

[6] Q. Qi, T. L. Geers "Evaluation of Perfectly Matched Layer for Computational Acoustics" *Journal of Computational Physics*, Vol. 139, No. 1, January 1998, 166-183

[7] M. Kaltenbacher, 2007, *Numerical Simulation of Mechanical Sensors and Actuators,* Springer, Berlin, Germany, 139-235

[8] A. Hackl, P. Hamberger "Investigation of Surface Velocity Pattern of Power Transformers Tanks", *2010 International Conference on Electrical Machines*, Rome, Italy