Numerical analysis of fluid-structure-interactions and resulting directional noise field of distribution transformers

Michael Ertl [1]

[1] *Siemens PTD Transformers Technology & Innovation, Nuremberg, Germany, Email: michael.ertl@siemens.com*

Abstract

This paper describes a numerical analysis of the fluid-structure interactions associated with magnetostrictive noise emission of oil immersed, core-type distribution transformers. The acousto-mechanical properties and the directional noise transmission are investigated, starting from the vibrating transformer core via the oil and tank structures to the surrounding air. Simulation results are verified by noise and tank surface vibration measurements.

Introduction

Magnetostrictive vibrations inside grain oriented electrical steel of laminated transformer cores cause the typical audible humming noise emission of transformers, known as no-load noise [3].

This source of sound is immersed in an oil-filled tank. The thin-walled tank acts as a acoustic membrane with poor acoustical properties. An improvement of the sound behaviour starts from an understanding of the sound wave propagation inside the fluids and solids and their mutual interactions. Following modal analyis, sensitivity analysis and parameter variations using numerical methods allow to identify and remove acoustical flaws.

Combined vibration and sound measurements

Combined measurements of the core surface vibration by using a Laser-Doppler-Vibrometer (LDV) and the directional sound emission by using a sound intensity probe were applied. A significant correlation of local vibration velocity and distinctive directional noise emission can be determined, both in amplitudes and frequency components. The transient signals of the core surface velocity are used as vibrational boundary conditions for subsequent numerical vibro-acoustical investigations.

To identify the sound transmission behaviour of the oil-filled tank unit, sound measurements of the vibrating core in air and the same sound source within the final assembled transformer are compared at the same induction level. A local relative rise of higher frequency components (500Hz, 600Hz) in the sound signal can be identified as a excitation of mechanical resonances within the thin-walled cooling fins.

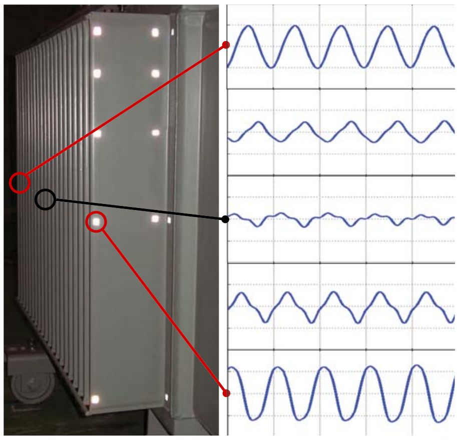

Figure 1: LDV measurement results of the transformer tank vibration at nominal core induction: Increased vibration amplitudes of the cooling fins towards the tank edges.

Modelling and calculation scheme

To allow a full three-dimensional transient calculation of the vibroacoustics, the finite element discretization of all transformer sub-structures has to be strongly optimized. Unstructured tetrahedral mesh generation based on *CAD*-data import would result in a large model size with bad mesh quality and is not appropriate. Instead, scripting based structured mesh generation with hexahedral elements is used to ensure high quality element shapes and to get full control of the model size.

Applying displacement based finite element formulations in the transient or modal analysis of thin structures will lead to geometric shear-locking phenomena. Depending on the element aspect ratio and the shape function used, parasitic shear-stresses will appear, leading to an artificial increase of the bending stiffness [2]. A locally refined mesh within the thin-walled transformer tank structures is used to minimise this effect.

A finite element calculation scheme based on the linearised acoustic wave equation and *Naviers* linearised theory of elasticity is used for a transient analysis of the presribed fluid-structure-interactions [1].

Tank surface and fin vibration behaviour

Distribution transformers with corrugated side walls feature cooling fins, which can be seen as fluid-filled sandwich plates with fixed edges (Fig.1). Adjacent fins are jointed to each other by the tank wall at the inner side and the stiffening bars at the outer side. Owing these mechanical connection, the fins of a tank side undergoes coupled motion instead of independent vibrations with direct consequence to the local and directional sound emission.

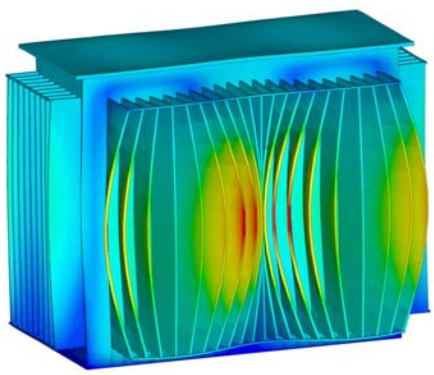

Figure 2: Bending mode 12 of oil filled tank at 330Hz.

An eigenfrequency analysis of the oil-filled tank using a quadratic eigenvalue solver (Arnoldi-Algorithm) gives insight in the basic mode shapes and resulting resonant vibration behaviour. Except some torsional modes, most of the lower eigenfrequencies show bending mode shapes of the corrugated tank. Remarkable is the large deflection of the outermost fins in some dominant modes (Fig. 2).

Furthermore, the tank wall deflections caused by the magnetostrictive vibration of the core are investigated at the centre position of each tank side between the cooling fins (Fig. 3). In a transient simulation including the fluid-structure-interactions core-oil-tank, vibrational restraints are performed to 19 representative core surface locations. Herbeby, the measured core vibration signals are used as the source of sound. It has to be noticed that the vibration behaviour of the oil-immersed core is slightly different than the measured vibrations without the surrounding oil. This is because of the added mass and the damping of the oil as well as the "gluing"-effect of the oil within the gaps of the core laminations at the main magnetostriction freuqency of 100Hz.

The resulting deflections of the corrugated tank coincide with the measured increased displacement of the cooling fins towards the tank edges (Fig. 3). In opposite to the expected overall vibration behaviour, the simulation as well as the measurements show larger deflections of the tank surface at the centre of the narrow side of tank wall in comparison with the centre of the wide side. From the geometric dimensions of the later one a more flexible behaviour with larger central displacements has been expected.

Directional sound emission behaviour

The observed increased fin vibrations towards the tank edges coincide with local maxima of sound intesity level at these edges - in simulation as well as in measurement. Hereby, the sound intensity in the simulation is derived from the acoustic vector potential of the fluid element, which represents the surrounding air around the transformer tank. The calculation is done at virtual microphone locations which are identical with the real microphone positions. (Fig. 4).

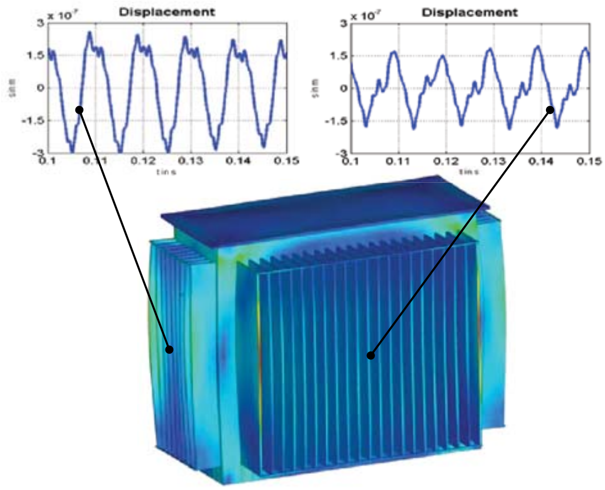

Figure 3: Transient analysis of fluid-structure coupling: Vibrational displacement of corrugation tank wall

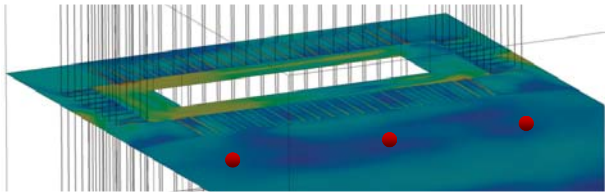

Figure 4: Sound wave propagation: Calculated sound pressure distribution and virtual microphone positions (dots).

Conclusions

The numerical simulation of the fluid-structure interactions based on measured core vibration data reproduce the measured vibrational behaviour of the tank as well as directional noise emission characteristics with sufficient accuracy. The calculated sound levels show deviations in range up to 5dB and needs further investigations.

References

[1] Kaltenbacher, M.: Numerical Simulation of Mechatronic Sensors and Actuators, Springer, Berlin, 2004.

[2] Koschnick, F.: Geometrische Locking-Effekte bei Finiten Elementen und ein allgemeines Konzept zu ihrer Vermeidung, Dissertation, TU München, 2004

[3] Moses, A.: Measurement of Mangetostriction and Vibration with Regard to Transformer Noise, IEEE Trans. On Magn., Vol. Mag-10, No. 2,1974