Numerical analysis and vibro-acoustic improvement of a thin-walled power transformer tank

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Introduction

Oil-immersed power transformers tanks with characteristic dimensions in range of 3-13m made up of rib-stiffened thin steel plates with a characteristic wall thickness of 10mm. This cost-optimised tank design shows disadvantageous vibro-acoustic properties. Mechanical resonances of tank fields can regularly identified as a major contributor of an increased noise emission above the expected design level (Fig. 1). The response of this fluid-loaded structure is dominated by the resonance modes if exposed to a periodic excitation [1, 2]. A noise-reduced transformer design needs to eliminate this vibro-acoustic flaws.

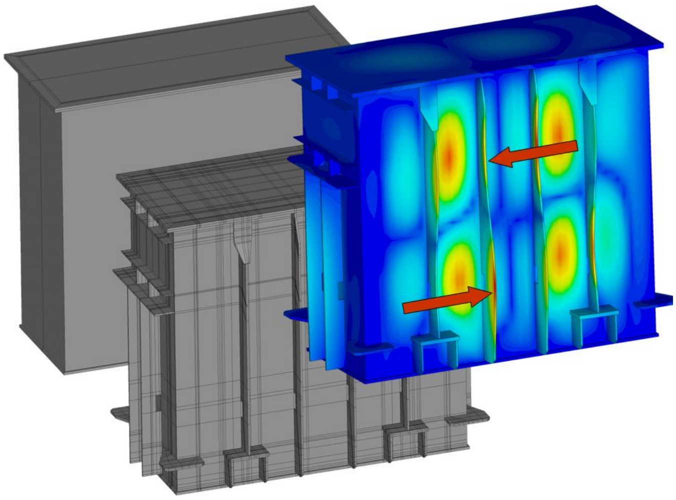

Figure 1: Bottom-up structured modelling of oil-immersed transformer tanks (left). Resonant sound transmission with strong lateral vibration of tank stiffener (right).

In power transformer manufacturing the production of single-units or small series is dominant, having in common solely the same tank design guidelines and standardised substructures. This situation does not allow a time-consuming numerical or experimental investigation of each individual unit. Instead the need for a strategic approach of an automated, fast modelling and analysis procedure arises to improve varying tank designs to avoid resonant sound transmission.

Modelling and analysis environment

An efficient and accurate FEM-based analysis of the vibro-acoustical properties of thin-walled vessels requires an optimised structured hexahedral mesh of high quality. Further, an accurate geometric model needs to include all structural details which affects the overall dynamic response of the system (Fig. 2). To reach reasonable computational costs, the model size has to be minimised as far as possible. These demands are contrary to the need for a fast and robust analysis tool for daily use in the design process.

Currently, no usable mesh generator is available to allow a hexahedral meshing of complex geometric structures based on imported CAD-data which meets the above prescribed requirements. The solution is a highly automated and parameterised bottom-up model generation based on geometry data transfer via interfaces to existing construction tools. Therefore the MATLAB environment is used to define and setup a virtual model geometry with a continuous structured mesh based on all defined tank substructures (Fig. 1). This parameterised and script based geometry setup gives the necessary flexibility for automatised design parameter variations, which are the base for design improvement or optimisation algorithms. The continuous fluid-element mesh within the oil-filled tank is generated simultaneously without any further bottom-up modelling efforts for the analysis of the fluid-structure interaction.

Using text files as interfaces, the geometric setup is used to generate and analyse the FEM-model within the ANSYS-CAPA environment. This method gives full control about the mesh structure. Thus, geometric shear-locking phenomena can be reduced by limiting the ratio of element side dimensions. After applying a harmonic frequency response analysis by distributed local force excitation at the transformer tank, the calculated nodal displacements are transferred back to the MATLAB environment for a fast postprocessing of the level of structure-borne sound (SBS). The SBS-level can be derived from the surface normal vibration of the tank and is defined as

$$L_{SBS} = 10\, lg \frac{S\, \overline{v_\perp^2}}{S_0\, v_0^2}. \qquad (1)$$

In (1), S denominate the total tank surface, $\overline{v_\perp^2}$ the time- and space- averaged mean-squared normal velocity of the tank surface and $S_0\, v_0^2$ is an appropriate reference value. The SBS-level can be taken as a measure of the vibrational sensitivity of a structure when exposed to mechanical loads and further as an estimator of the total sound transmission behaviour of the transformer tank [3, 4].

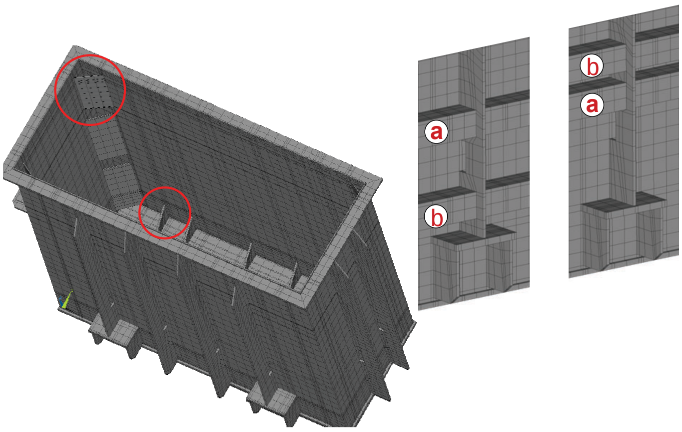

Figure 2: Detailed hexahedral meshing of oil-filled transformer tank (left). Parametric change of stiffener positions within the vibro-acoustic improvement routine (right).

Vibrational behaviour of fluid-loaded tank

The numerical frequency response analysis shows the typical high mode density of thin-walled power transformer tanks (Fig. 3). Comparing the frequency response of an "empty" tank structure with the one-sided fluid-loaded tank, the additional fluid mass loading strongly lowers the natural frequencies. Hereby the structural mode shapes remain unchanged in most cases. If the principal dimensions of the confined fluid volume meets the dimensions of standing waves within this cavity, coupled fluid and structural mode shapes can be observed.

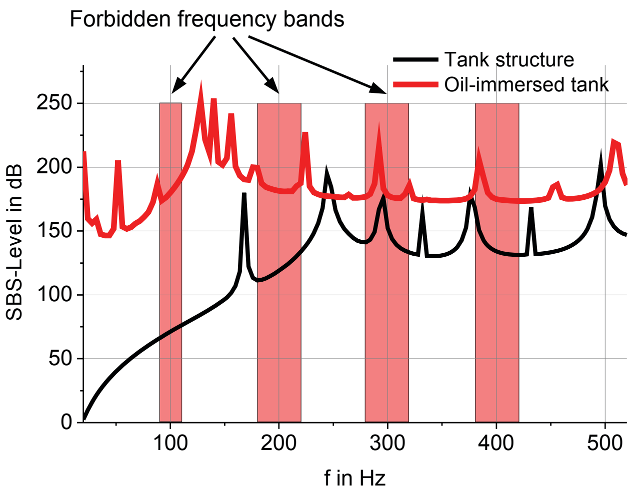

Figure 3: Frequency response of an oil-filled and empty transformer tank. The forbidden frequency bands surrounding the excitation frequencies are highlighted.

Design improvement procedure

The parameterised model allows a fast change of any substructure within the iterative vibro-acoustic improvement process. Using the number and position of stiffeners as the variation parameters, the optimisation parameters are the natural frequencies. The target is to shift the natural frequencies of the oil-immersed tank outside the "forbidden" frequency bands. These frequency bands surrounds the excitation frequencies of the transformer humming noise (fundamental frequency of 100Hz and higher harmonics) (Fig. 3). As an improved design is considered if the mean SBS-level L_{SBS_tot} within all forbidden frequency bands is distinctly reduced (3-4dB(A)).

Hereby the optimisation design space at the tank surface is restricted, e.g. regions for fittings are excluded. Further restriction are mainly based on assembly and cost considerations. Thus, only horizontal and vertical row- and cross-stiffening can be applied. Because of this widely restrictions, no mathematical optimisation algorithms are applied so far. Instead the results of the parameter variation process are used as a base for the decision process of the engineer to evaluate an appropriate design for the final tank structure.

Typical processing times for a frequency response analysis using 80 000 finite elements are $< 1h$ for modelling and meshing, $3h$ for the frequency response analysis of 50 frequencies and $< 1h$ for post processing

Conclusions

Sound emission of power transformers is increased in case of resonant sound transmission of the thin-walled transformer tank. The resonance frequencies of tanks filled with a heavy fluid (mineral oil) are far from the in-vacuo frequencies. Thus, a vibro-acoustic optimisation of this devices needs to consider the strong coupled fluid-structure system. The presented automatised, script-based modelling and analysis routine allows to avoid vibro-acoustic flaws in advance. The accuracy and computational costs are suitable for daily use to improve transformer tank design.

References

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