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Modeling and Experimental Verification of Ultrasound Transmission in Electro Insulation Oil

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A verification study of ultrasound transmission numerical simulation results with experiment results is presented in this paper. The work considers a model of a transformer tank which is filled with electro insulating oil. In the experiment, performed under laboratory conditions, an ultrasound wave is generated by a piezoelectric transducer that is fixed in the centre of the tank and measured by another transducer mounted inside the tank at three distances: 10, 20 and 30 cm from the sound source. The transducer is able to measure and generate acoustic waves in the ultrasound frequency band up to 1 MHz. The simulation considers numerical calculation of acoustic pressure distribution inside the tank in which acoustic source emits waves with frequency equal to 100 kHz. Verification analysis has confirmed consistency of the numerically calculated values with the measurement results.

Keywords: ultrasound transmission, numerical simulation, electro-insulation oil.

1. Introduction

Currently, the acoustic emission (AE) method is widely applied in the oil immersed power transformer partial discharge (PD) diagnostics (Boczar *et al.*, 2009; Cichoń, 2009). The AE method is based on AE signal measurements performed by use of transducers that are preferably mounted on the transformer surface. Due to a complicated construction of power transformers, research work mainly considers simplified models depicting steal tanks filled with oil in which PD sources are mounted. In these studies, the acoustic wave propagation phenomena are investigated (Wotzka, Boczar, 2010a; Wotzka, 2011). The aim of the research performed by the authors is to determine an acoustic numerical model of the insulation system in order to improve and simplify research regarding a PD diagnosis in oil immersed electric power transformers. In particular, the work performed pursues elimination of a high voltage which is applied for PD generation in the spark gaps. The overall goal is to enable research performed on a personal computer by use of numerical acoustic emission wave simulators.

A number of experiments and simulations performed by use of a commercial tool, the COMSOL Multiphysics, have been performed during the research. (Wotzka *et al.*, 2009; 2010; Wotzka, Boczar, 2010b). In this paper, results of numerical calculations are verified with data gathered in experiments performed under laboratory conditions.

2. Experimental setup and measurements results

The measurement setup consisted of: a filled with electro-insulating oil transformer tank with dimensions of 60 cm × 60 cm × 70 cm, two electro-mechanical (piezoelectric) transducers, PIC 155 from PI Ceramic, a preamplifier, AE signal conditioner from EA Systems, a digital oscilloscope HandyScope HS3 from Tie Pie with two measuring inputs and one generator output, and a personal computer (PC). The piezoelectric transducer and the transformer tank, applied in the experiments, are presented in Fig. 1. One of the transducers generated a sinusoidal acoustic signal of the frequency changing in the range from 1 kHz to 1 MHz with a step of 1 kHz for each run. The signal shape was defined at the PC and transferred via a USB cable to the digital oscilloscope generator channel, and from there it was forwarded to the transducer and emitted inside the tank. The amplitude of the signal generated, 3 V, was selected for best measurement results, e.g. for the signal amplifier not to be overdriven. The acoustic

Fig. 1. View of the transformer tank and the transducer applied in the experiments.

signal was measured by the second transducer at three distances: 10, 20 and 30 cm respectively, and forwarded through the preamplifier to the digital oscilloscope and from there to the PC, where it was later analysed. Both transducers were mounted on a cooper sticks and fixed to a bakelite plate (see Fig. 1).

In Fig. 2, an analysed signal amplification in dependence of the frequency at three distances is presented. The values are calculated by a division of the measured signal amplitude by the generated signal amplitude $A_{\text{pom}}/A_{\text{gen}}$ [V]. The signal amplitude is larger in the frequency range below 60 kHz. One can also recognize that the signal decays with distance. Further, characteristic fluctuations of the signal in the vicinity of the resonance frequencies 115, 208, 280, 305, 365 kHz are recognized.

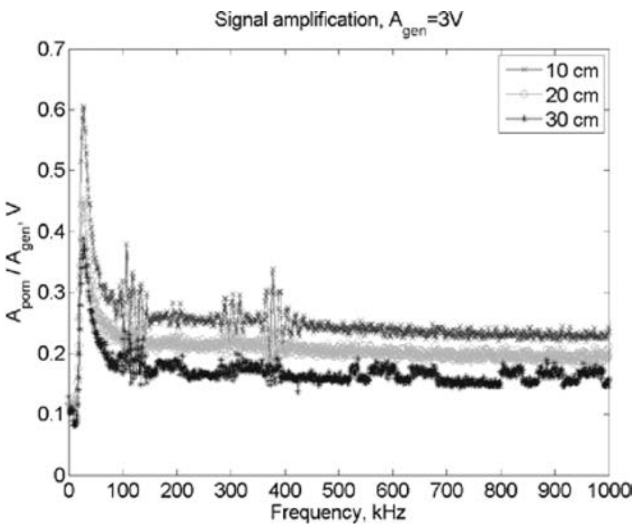

Fig. 2. Dependence of the signal amplitude measured at three distances versus the generation frequency.

Some numerical example values of the measured signal amplitude A_{pom} for selected frequencies are presented in Table 1. From Table 1 it is clear that the amplitude is smaller for higher frequency signals than for lower frequency ones. This phenomenon is similar to the electromagnetic wave behavior, namely, attenuation of high frequency signals in the propagation medium.

Table 1. Example results of the signal amplitude A_{pom} [V] measured at the analysed distances, while generating sinusoidal waves at selected frequencies.

Distance [mm]	A_{pom} [V]			
	150 [kHz]	250 [kHz]	550 [kHz]	930 [kHz]
10	1.5430	1.5332	1.4648	1.3379
20	1.3281	1.2988	1.2207	1.1426
30	1.0645	0.9961	0.9473	0.8984

3. Numerical model definition and simulation results

Acoustic pressure distribution p, Pa inside the transformer tank has been evaluated numerically in the COMSOL Multiphysics environment. The simulation uses a linear PDE solver. To reduce the numerical complexity, the model geometry has been simplified to two-dimensions, where additionally a symmetry axis has been adopted. The model applied in the numerical calculations whose results are analysed in this paper is presented in Fig. 3.

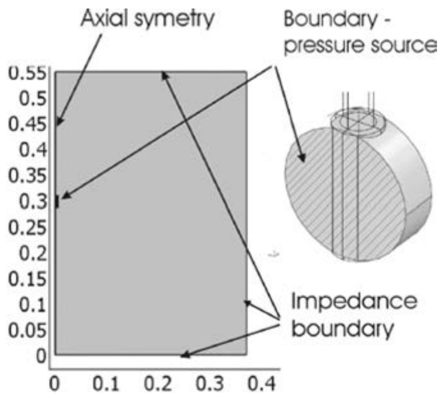

Fig. 3. Two dimensional models used in the numerical calculations and specified boundary conditions.

The boundary conditions are crucial for the simulation results and were specified as follows:

1) on all tank exterior boundaries, the impedance boundary condition (Robin boundary condition) was defined as $Z = 123.7 \times 10^4$ kg/m^{2}s,
2) at the boundary between oil and transducer emitting side, the sinusoidal pressure changes are defined (Dirichlet boundary condition) as follows:

$$p = A\cos(2\pi ft),$$

where $A = 1 \times 10^4$ Pa, $f = 100$ kHz.

The oil filling the tank has the following parameters: density $\rho_0 = 890$ kg/m^3, speed of sound $c_s = 1390$ m/s. The initial values modeled are as follows: $p(t_0) = 0$ and $\partial p/\partial t(t_0) = 0$. The verification analysis considered the steady state of the acoustics pressure distribution when the sound was emitted with the frequency $f = 100$ kHz and wavelength $\lambda = 13.9$ mm. The largest mesh element size did not exceed 2.78 mm, and the number of degrees of freedom was equal to 229019.

In Fig. 4 the acoustic pressure distribution in the transient state is presented: after 20 signal periods (Fig. 4 left) and after 40 signal periods (Fig. 4 right), respectively.

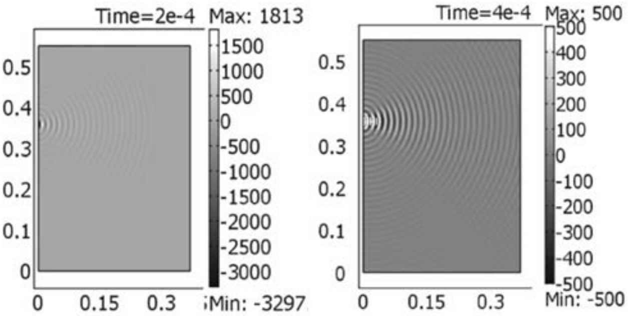

Fig. 4. Acoustic pressure distribution in the tank after 20 periods (left) and after 40 periods (right).

In Fig. 5 the acoustic pressure distribution in the steady state is presented. The highest amplitude values calculated, over 100 Pa, have been filtered, so that the differences in the space distribution are better to see. The brightest places have the highest amplitude. One can see that the pressure amplitude attenuates rapidly in the vicinity of the sound source.

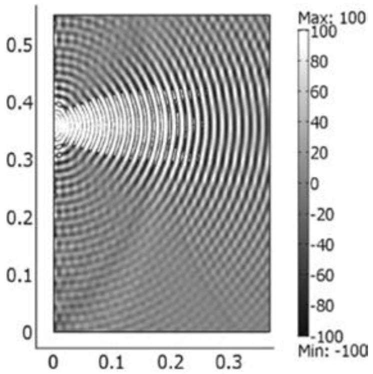

Fig. 5. Acoustic pressure distribution in the tank in the steady state (after 60 periods).

4. Verification results

In this paper we analyse only the data gathered during measurements in which the sinusoidal acoustic signal was generated with the frequency equal to 100 kHz. Data gathered during the measurements has been compared to the data gathered from the numerical calculations. Amplitude values from both signals (the measured and simulated) have been normalized in order to simplify the verification process. Signal amplitude in dependence of distance is presented in Fig. 6. The simulated and the measured data are in good agreement.

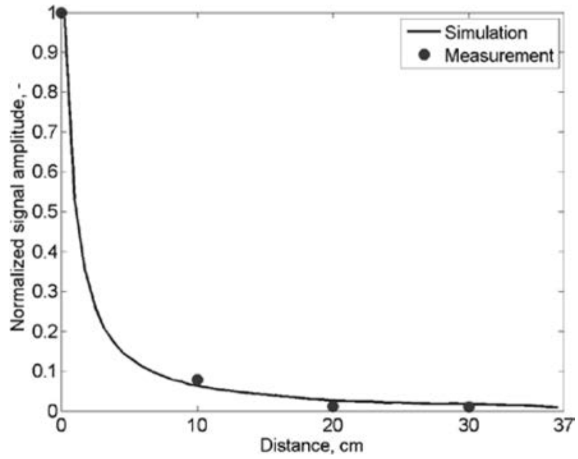

Fig. 6. Normalized amplitude values in dependence of the distance.

The normalized amplitude values gathered during the simulation and during the measurements at three analysed distances are depicted in Table 2 in a numerical form for comparison.

Table 2. Normalized values gathered from the experiments and simulation at the analysed distances.

Distance	0 [cm]	10 [cm]	20 [cm]	30 [cm]
Simulation	1	0.06655	0.02612	0.01649
Measurement	1	0.07828	0.01215	0.01008

Additionally, the dependency of the signal amplitude versus distance d [cm] was analysed by use of standard fitting tools supported by MATLAB. The functional dependency $f(d)$ can be described by Eq. (1) which presents an exponential regression model.

$$f(d) = \alpha_1 e^{\beta_1 d} + \alpha_2 e^{\beta_2 d}. \tag{1}$$

The coefficients α_1, α_2, β_1, and β_2 have been calculated with 95% confidence bounds as presented in Table 3.

Table 3. The estimates with the confidence bound calculated for the regression model.

Coefficient	α_1	β_1	α_2	β_2
Estimate	0.9803	-0.03596	0.2065	-0.00387
Upper bound	1.007	-0.03383	0.2266	-0.003514
Lower bound	0.9537	-0.03808	0.1864	-0.004226

Goodness parameters calculated for the applied regression model are summarized in Table 4. The achieved values indicate a good fitting result.

Table 4. Goodness parameters of the regression model.

Parameter	SSE	R-square	RMSE
Value	0.003054	0.9977	0.007815

5. Discussion of the results and paper summary

Results of a verification analysis of acoustic signals propagating in a tank filled with electro-insulation oil have been presented in the paper. The work considered experiments carried out under laboratory conditions and numerical simulations performed by use of the COMSOL Multiphysics software. A short description of the measurement setup, simulation details, and exemplary results of both have been presented. The simulated data is in good agreement with the measurement results. Based on the results, it was confirmed that the acoustic signal amplitude attenuates with a growing distance. This dependency has been described by a mathematical regression function consisting of a sum of two exponential functions. Further, it has been confirmed that high frequency signals are attenuated more than low frequency signals. In further studies, numerical simulations of a tridimensional object will be considered.

Acknowledgments

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References

1. Boczar T., Borucki S., Cichoń A., Zmarzły D. (2009), *Application Possibilities of Artificial Neural Networks for Recognizing Partial Discharges Measured by the Acoustic Emission Method*, IEEE Transactions on Dielectrics and Electrical Insulation, **16**, 1, 214–223.

2. Cichoń A. (2009), *The Application of the Selected Time–Frequency Descriptors Detection of the Acoustic Emission Signals Generated by Multisource Partial Discharges*, Acta Physica Polonica A, **116**, 3, 290–293.

3. Wotzka D. (2011), *Modeling of acoustic emission signals generated by chosen classes of partial discharges* [in Polish: *Modelowanie sygnałów emisji akustycznej generowanej przez wybrane klasy wyładowań niezupełnych*], Ph.D. Thesis, Opole University of Technology, Poland.

4. Wotzka D., Boczar T. (2010a), *Analysis of acoustic emission signals in power transformer model* [in Polish: *Analiza sygnałów emisji akustycznej w modelu transformatora elektroenergetycznego*], Electrical Review, **11b**, 74–77.

5. Wotzka D., Boczar T. (2010b), *Analysis of AE signals generated by piezoelectric transducer in a transformer tank model* [in Polish: *Analiza sygnałów EA generowanej przez przetwornik piezoelektryczny w modelu kadzi transformatorowej*], Pomiary Automatyka Robotyka, **12**, 84–89.

6. Wotzka D., Boczar T., Zmarzły D. (2009), *Analysis of acoustic wave propagation in a power transformer model*, Acta Physica Polonica A, **116**, 3, 428–431.

7. Wotzka D., Boczar T., Zmarzły D. (2010), *Numerical simulation of a sinusoidal acoustic wave that propagates in a spherical object filled with transformer oil*, Acta Physica Polonica A, **118**, 6, 1272–1275.