

Active Noise Reduction of Transformer Core Vibration Using Reverse Frequency Coupling in Multiphysics Simulation

Naming Zhang¹, Yuanchao Wang¹, Ziyang Chen¹, Wenhan Zhang¹, Siying Yang¹, Yangcheng Liu¹, Shuhong Wang¹ and Shuya Ning²

¹ The School of Electrical Engineering, Xi'an Jiaotong University, Xi'an, 710049, China;

² The School of Electronic Information and Artificial Intelligence, Shaanxi University of Science and Technology, Xi'an, 710021, China

Transformer core noise primarily results from the magnetostrictive effect, where slight deformations during magnetization generate mechanical vibrations and noise. This study employs COMSOL simulation for multi - physics analysis, integrating magnetic field, structural mechanics, and acoustics, to analyze the vibration and acoustic field distribution in a 200 kVA laminated core transformer, focusing on noise generation mechanisms and their environmental impact. An active noise control (ANC) system is proposed to mitigate the noise, utilizing inverse frequency vibration to neutralize core-induced vibrations. Through simulation and comparative analysis, the ANC system effectively reduces noise, improving the transformer's acoustic performance and minimizing its environmental impact.

Index Terms—Active noise reduction system; Magnetostriction; Iron core vibration; Finite element method.

I. INTRODUCTION

With the increasing capacity of power systems, transformer-generated noise pollution significantly impacts the environment and quality of life. The vibration noise issue of transformers requires urgent study and resolution. The active noise control (ANC) system uses inverse frequency vibration for noise neutralization, effectively reducing impact.

Some studies have explored the application of active noise control systems. Tao Su et al^[1] developed a transformer feature analysis method based on acoustic interference, with the ANC system effectively reducing noise. J Yu et al^[2] investigated real-time active noise control for 10 kV substation noise suppression, achieving effective noise reduction. However, a comprehensive analysis of transformer-generated noise and the deployment of ANC systems for noise reduction in complex propagation path scenarios still requires further in-depth research.

This study combines magnetic field, structural mechanics, and acoustics simulations for a transformer to analyze vibration and acoustic field distribution. An ANC system using inverse frequency vibration effectively reduces noise impact.

II. TRANSFORMER CORE VIBRATION MODEL

A. Transformer geometric model

This study models a 200 kVA laminated core transformer, with parameters listed in Tab.1. The transformer's six corners are sequentially numbered, as shown in Fig.1.

TABLE I
TRANSFORMER MODEL PARAMETERS

Item	Type Size
Capacity /kVA	200
Core window height H/m	0.22
Core center distance Core column cross-sectional area M ₀ /m ²	0.385
Voltage rating/kV	10/4
High and low voltage turns	1775/41

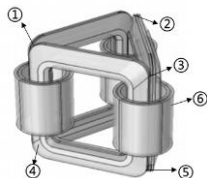


Fig. 1. Simulation model of a 200 kVA laminated core transformer.

B. Electromagnetic field computation

A 10 kV, 50 Hz three-phase AC voltage is applied to the primary side, with the secondary current set to 0 for no-load operation. The primary voltage^[3] is expressed as follows:

$$U_A = U_N \sin(2\pi f \cdot t - \frac{2}{3}\pi), U_B = U_N \sin(2\pi f \cdot t), U_C = U_N \sin(2\pi f \cdot t + \frac{2}{3}\pi) \quad (1)$$

Magnetic field control equations and boundary conditions:

$$\nabla \times \frac{1}{\mu} (\nabla \times \mathbf{A}) = \mathbf{J}_s - \sigma \frac{\partial \mathbf{A}}{\partial t}, \mathbf{B} = \nabla \times \mathbf{A} \quad (2)$$

$$\mathbf{A}|_{\Gamma_1} = g(\Gamma_1), \frac{\partial \mathbf{A}}{\partial \mathbf{n}}|_{\Gamma_1} = g(\Gamma_1), \left(\alpha \mathbf{A} + \frac{\partial \mathbf{A}}{\partial \mathbf{n}} \right)|_{\Gamma_3} = g(\Gamma_3) \quad (3)$$

μ denotes magnetic permeability, $\mathbf{A}$ represents magnetic vector potential, $\mathbf{J}_s$ is source current density, σ is electrical conductivity, and $\mathbf{B}$ is magnetic flux density.

C. Magneto-mechanical coupling force field computation

Transient electromagnetic analysis yields the time - dependent core electromagnetic force. Magnetostrictive strain is computed by substituting simulated magnetic flux density $\mathbf{B}$:

$$\lambda = \lambda(\mathbf{B}) \quad (4)$$

In the equation, magnetostrictive strain $\lambda(\mathbf{B})$ of amorphous alloy vs. flux density is from curve. $\lambda(\mathbf{B})$ in the silicon steel is converted to stress, which excites core vibration, the differential equation is solved to obtain node displacements.^[4]

$$\sigma = D\lambda, -F_v = \nabla \cdot \sigma \quad (5)$$

$$M \frac{\partial^2 \mathbf{u}}{\partial t^2} + C \frac{\partial \mathbf{u}}{\partial t} + K\mathbf{u} = F_v \quad (6)$$

D is the elasticity matrix, F_v is the equivalent magnetostrictive force, M is the mass matrix, C is the damping matrix, D is the stiffness matrix, and $\mathbf{u}$ is node displacement.

D. Acousto-mechanical coupling sound field computation

The domain equation for the sound field is as follows:

$$\frac{1}{\rho_0 c^2} \frac{\partial^2 p}{\partial t^2} - \nabla \cdot \left(-\frac{1}{\rho_0} \right) (\nabla p - F_v) = Q \quad (7)$$

p is sound pressure, ρ_0 is fluid density, c is sound speed, and Q is sound source. Acousto-mechanical coupling equations and sound pressure to level conversion(L_p):

$$-n \cdot \left(-\frac{1}{\rho_c} (\nabla p - q_d) \right) = -n \cdot \mathbf{u}_n, L_p = 20 \lg \frac{p}{p_0} \quad (8)$$

Here, $\mathbf{n}$ is the unit normal vector on the surface, ρ_c is the density of the medium, $\mathbf{q}_d$ is the particle velocity vector, $\mathbf{u}_{it}$ is the displacement normal acceleration. L_p is the sound pressure to level conversion. p_0 is the reference sound pressure.

III. TRANSFORMER MODEL WITH ANC SYSTEM

A. Model construction

This study investigates noise reduction for a 200 kVA three-dimensional wound core transformer using an ANC system, which emits anti-phase plane waves around the transformer. Noise levels at 11.25 m are analyzed to simulate the impact of a small distribution substation on nearby residential buildings.

B. ANC system parameter settings

Based on Fig.2's workflow, an ANC system is installed near the transformer facing residential areas. FFT shows 100 Hz as dominant noise frequency. Plane wave sources simulate the ANC system's effect.

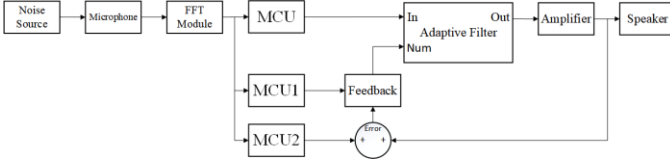


Fig. 2. ANC system block diagram

IV. SIMULATION RESULTS

A. Magnetic field and force field vibration displacement calculation results

The transient solution of the electro-magnetic-structural field is obtained using a fully coupled solver, resulting in the magnetic flux density distribution in the core, as shown in Fig. 3.

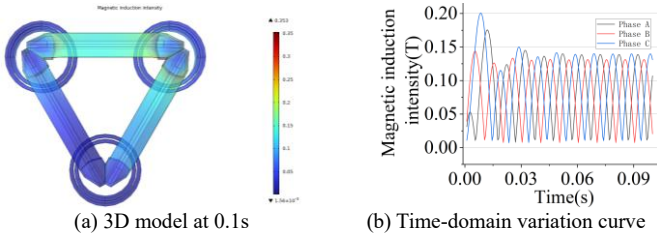


Fig. 3. Magnetic flux density under no-load operation of the transformer.

Points are selected at the top, corners, upper yoke, side, and core column to calculate vibration displacements, with time-domain and frequency-domain variations shown in Fig.4.

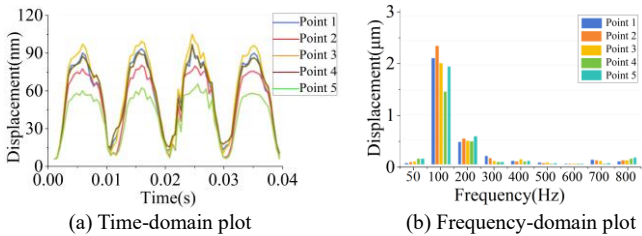


Fig. 4. Transformer no-load vibration displacement.

As shown, the transformer's no-load vibration displacement shows periodic variation at a primary frequency of 100 Hz.

B. Effect of ANC System on Transformer Core Noise

The study employs a 100 Hz sinusoidal anti-noise wave with an amplitude of 0.0005 Pa and a phase of 0. Figure 5 illustrates

the impact of applying and not applying the plane wave on noise levels at residential buildings, showing the variation in sound pressure levels over time at three points, labeled as A, B, and C.

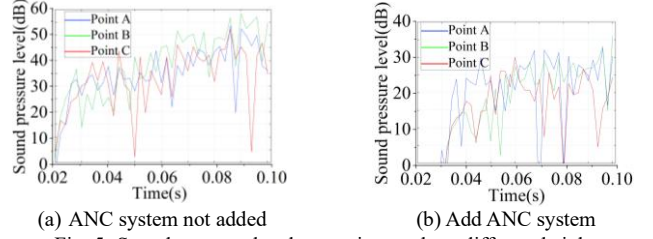


Fig. 5. Sound pressure levels over time at three different heights.

As shown, without the ANC system, transformer noise at the residential buildings ranges from 30 to 60 dB, peaking at 58.304dB. With the ANC system, noise is reduced to 15–35 dB, with a maximum of 35.737 dB, indicating a reduction of 22.567 dB in peak sound pressure level.

C. Impact of Anti-Noise Wave Amplitude on Noise Levels

To analyze residential noise variations caused by transformer amplitude changes, this study used sinusoidal plane waves of varying amplitudes from the ANC system. Figure 6 shows sound pressure levels at three heights and the maximum across the plane at 0.1 seconds.

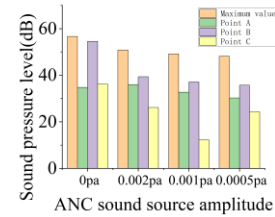


Fig. 6. Maximum Plane and Point A, B, C Sound Pressure Levels with Different Source Amplitudes at 0.1s.

Simulations show that all three source amplitudes reduce residential noise levels. Without the ANC system, the max plane noise is 56.66 dB. With the system, maximum levels are 50.85 dB (0.002 Pa), 49.19 dB (0.001 Pa), and 48.21 dB (0.0005 Pa), indicating smaller amplitudes achieve better noise reduction.

V. CONCLUSION

A simulation model for transformer core vibration noise was developed. The ANC system with inverse frequency vibration effectively reduced noise impact on the environment.

ACKNOWLEDGEMENT

This work was supported by the National Key R&D Program of China (2022YFB2403600).

REFERENCES

- [1] Su T, Sun H, Guo Z. *Transformer behavior feature identification and analysis technology based on acoustic interference*. Journal of Physics: Conference Series. 2022;2310(1):012051.
- [2] Yu, J.; Zheng, Z. et al *An Investigation of Real-Time Active Noise Control for 10 kV Substation Noise Suppression*. Sustainability 2023(15), 13430.
- [3] Cui Jiajia, Ma Hongzhong, et al. *Finite element simulation of the transformer core vibration sound field distribution based on COMSOL*. Journal of Electronic Measurement and Instrumentation, 2022, 36(4): 48-55.
- [4] Y. Cai and A. Hou. *Analysis on transformer vibration signal recognition based on convolutional neural network*. Journal of Vibroengineering, Vol. 23, No. 2, pp. 484–495, Feb. 2021.