Acoustic radiation efficiency parameter in assessment of transformer noise

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Summary

Electrical apparatus such as transformers radiate noise which is almost completely harmonic in its frequency characteristic and stationary in the time domain. Those two parameters enable us to look at the transformer noise through its vibration pattern of the tank wall structure. In contrary to calculating sound radiation efficiency from noise and vibration data, using only vibration data has a big advantage - the results are independent of ambient noise and acoustic parameters prediction can be performed on the design stage. However, no standards describing this approach are available at the moment. Laser Doppler Vibrometry (LDV) technique is used to identify vibration velocities of the transformer tank. The LDV measurement is non-contact and therefore the tested surface remains not influenced during the measurement. This is a big advantage of the method which provides capability for power products to be energized during the test. Eventually, the device can be measured directly during its operation and the vibration pattern information is much more reliable. Three methods of calculating acoustic radiation efficiency parameter are tested and evaluated on a 250 MVA power transformer. Comparison in between methods and results for transformer units conclude the research.

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1. Introduction

The aim of transformer working in power system is to convert electrical energy in a mostly lossless way. Due to many side effects of the energy conversion process in a transformer that reduce the performance of the device, noise as environmental impact is one of the negative results whose limitation is nowadays an important aspect. A well-known effect, almost inherently related to the work of the transformer, is a hum noise. The transformer noise is mainly caused by physical phenomena occurring in the core and windings. Two operating conditions can be generally distinguished when a power transformer is running in the energy grid, namely: load and no-load conditions. Both are strictly followed by the noise generation: a not loaded power transformer emits only the noise caused by magnetostriction of the magnetic core, in load condition Lorentz forces inside the windings dominate. The noise which occurs in the subsequent operating mode differs by its frequency spectrum. Load and no-load noise of the transformer is strictly harmonic with the difference in the dominant frequency. An exemplary noise spectrum at load condition for a power transformer is shown in Figure. 1.

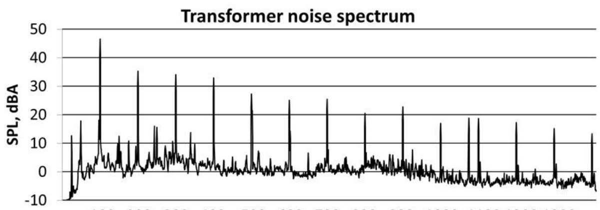

Figure 1. Transformer noise spectrum at load conditions.

This work presents an approach to characterize the transformer noise source quality with the radiation efficiency parameter.

2. Radiation efficiency

Radiation efficiency (other names: radiation factor, radiation ratio, radiation index) is a quantity that characterizes the efficiency of a given vibrating surface as a sound radiator [1]. It is a fundamental parameter to describe the coupling between structural waves propagating in a vibrating element with the structure born noise [2] [3].

The radiation efficiency σ is given by the formula [1]:

$$\sigma = \frac{W_{rad}}{\rho_0 c_0 S \langle \bar{v}^2 \rangle} \tag{1}$$

where:
W_{rad} – sound power radiated from one side of a vibrating surface, having the area S $[W]$
ρ_0 - density of the medium $[kg/m^3]$
c – speed of sound $[m/s]$
S – area of the vibrating surface $[m^2]$
$\langle \bar{v}^2 \rangle$ - squared vibration velocity magnitude in $[{}^{m}/_{s}]$ and averaged over area S. Depending on the method, a RMS-value is used (method based on acoustic and vibration results, method based on the linear superposition of effects) or a peak value (Discrete Calculation Method).

The concept of radiation efficiency is present in many fields of engineering where noise control is an important issue. It is extensively used to characterize the radiation ability of vibrating plates carrying bending waves [4] – this problem appears in construction of machinery, buildings, electroacoustical devices, airplanes, cars [5]. According to [2], acoustic radiation efficiency is a good indicator for the transformer tank design sound quality.

An analysis of available literature has shown that there is a big number of works presenting various prediction formulas for sound radiation, such as Cremer [6], Maidanik [7], Wallace [8], Leppington [9], Laulagnet [10] or Putra [11]. However, most of analytical solutions presented in the literature are very complicated. Because of that, solving realistic sound radiation problems with a theoretical approach becomes very complicated or even impossible [12]. As a consequence, a number of works dealing with experimental evaluation of radiation efficiency have been published.

Revel [13] presented a vibration-based method for the sound power level determination. This article does not discuss radiation efficiency. However, it can be indirectly evaluated by substituting the sound power obtained from this method into the formula that defines radiation efficiency. Hashimoto [12] proposed a vibration-based method for radiation efficiency evaluation, called Discrete Calculation Method. It is derived with the help of Sir Rayleigh formula for the impedance of a rigid piston vibrating in an infinite rigid baffle. Kozupa [2] used the Discrete Calculation Method from [12]

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together with a laser Doppler vibrometer to evaluate radiation efficiency of a transformer tank wall. Kleiner [4] analysed the effect of the plate discretization level on results obtained with the Discrete Calculation Method.
According to [4], the acoustic radiation efficiency is used extensively to characterize the radiation ability of sheets carrying bending waves.
The analysis of the literature also resulted in a conclusion that the Discrete Calculation Method is the most popular vibration-based method for radiation efficiency determination. However, no simultaneous comparison of the method based on acoustic and vibration measurements with the vibration-based methods described by Hashimoto and Revel was found.

3. Method based on acoustic and vibration measurements

This method relies on substituting acoustic and vibration results into a formula defining the radiation efficiency (1). Two types of measurements must be performed in order to get the result:

- acoustic measurement – necessary to obtain radiated sound power, either by sound pressure or sound intensity measurement,
- vibration measurement – necessary to obtain vibration velocity, which can be measured e.g. with a laser Doppler vibrometer.

In this work, a sound intensity measurement was performed. The results were converted into a sound power level according to the formula:

$$L_{WA} = \overline{L_{IA}} + 10lg\frac{S_{meas}}{S_{ref}} \qquad (2)$$

where
$\overline{L_{IA}}$ – total spatially averaged A-weighted normal sound intensity level
S_{meas} – area of measurement surface
S_{ref} – reference area, S_{ref} = 1 $[m^2]$

The area of measurement surface was calculated as:

$$S_{meas} = (h + x)l_m \qquad (3)$$

where
h – height of the principal radiating surface [m]
x – measurement distance from the principal radiating surface to the prescribed contour [m]
l_m – length of the prescribed contour [m]

4. Discrete Calculation Method

The physical idea behind DCM consists in dividing the examined sound-radiating structure into rectangular elements each of which is further assumed to radiate sound as a rigid hard-baffled circular piston with the surface area equal to this of the corresponding virtual element (Figure 2). It is assumed that each rectangular element contributes to the total sound radiation power. The advantage of the method over conventional sound radiation efficiency measurement techniques comes in the fact that instead of acoustic pressure values, source (plate) vibration velocity amplitude values are measured in a selected number of regularly distributed points. In many cases, this allows to determine the sound radiation efficiency with sufficient accuracy, especially for the low frequency regime.

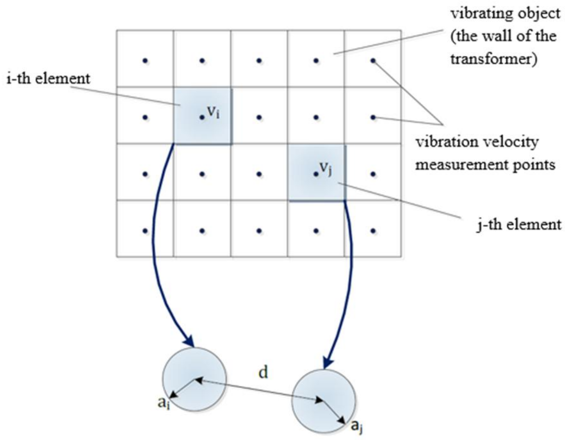


Figure 2. The idea of Discrete Calculation Method.

This virtual division opens up the possibility to use analytical expressions for a vibrating circular piston in order to calculate radiation efficiency of our vibrating. The radiation impedance related to each individual DCM element and each mutually interacting pair of elements is derived with the help of Sir Rayleigh formula for impedance of a rigid piston vibrating in an infinite rigid baffle [2]. The expressions are presented below:
Self radiation impedance:

$$z_{ii} = \rho c s_i \left[1 - \frac{J_1(2ka_i)}{ka_i} + j\frac{S_1(2ka_i)}{ka_i}\right] \qquad (2)$$

Mutual radiation impedance:

$$z_{ij} = \frac{\rho c k^2 s_i s_j}{2\pi}\left[2\frac{J_1(ka_i)}{ka_i}\right]\left[2\frac{J_1(ka_j)}{ka_j}\right]\left(\frac{\sin kd}{kd} + i\frac{\cos kd}{kd}\right) \qquad (3)$$

Radiation sound power:

$$W_i = \mathrm{Re}(z_{ii})|v_i|^2 + \sum_j Re(z_{ij} v_i v_j^*) \quad (4)$$

And finally, acoustic radiation efficiency:

$$\sigma = \sum_i \frac{W_i}{\rho_0 c S \langle \bar{v}^2 \rangle} \quad (5)$$

where

ρ – air density $[kg/m^3]$
c – speed of sound $[m/s]$
s_i, s_j – area of the i-th element, area of the j-th element $[m^2]$
J_1 – first-order Bessel function
k – the wave number of sound
a_i – equivalent radius of the i-th element when the rectangular element is appropriated by a circular element, $a_i = \sqrt{s_i/\pi}$ [m]
S_1 – Struve function
d – distance between the centers of two circular elements [m]
Re(...) - real part of a complex number
v_i, v_j – complex vibration velocities of the i-th and j-th elements, obtained as spectra by Fast Fourier Transform analysis of the measured velocity waveform
S - area of the vibrating surface $[m^2]$
$\langle \bar{v}^2 \rangle$ – mean square of the vibration velocity in $[m/s]$ averaged over S

5. Method based on linear superposition of effects

This method allows to estimate sound pressure level at any point in the front of the vibrating surface using only vibration velocity data. Then, sound power is estimated from the sound pressure level and substituted into equation 1.

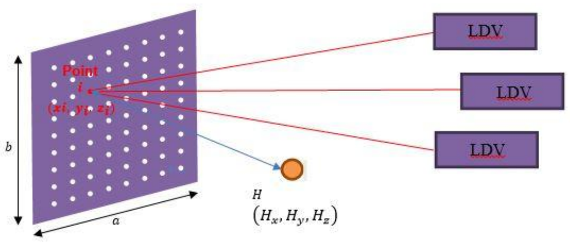


Figure 3. Method based on the linear superposition of effects – estimation of the sound pressure level in front of the vibrating surface.

The sound source is modeled by the radiation from a circular piston of area S, mounted flush with the surface of an infinite baffle and vibrating with simple harmonic motion. The authors of the method assumed that the piston is composed of an array of simple sources A_i. Each simple source corresponds to the portion of area with center in the vibration measurement point. Both magnitude/phase information and spatial distribution of the vibration data are taken into account.

Sound pressure at point H radiated by the i-th simple source A_i at the distance r_{iH} is calculated as:

$$p_{iH} = S_i \cdot \frac{j\rho c k}{2\pi r_{iH}} \cdot v_i \cdot e^{j(\omega t - k r_{iH} - \phi_i)} \quad (6)$$

where

S_i – emitting surface of the simple source A_i
v_i, ϕ_i – vibration velocity magnitude and phase measured in A_i

The total sound pressure p_H at point H is estimated by means of the linear superposition of effects. It means that contributions of all the elements A_i are summed:

$$p_H = \frac{j\rho c k}{2\pi} \cdot \sum_{i=1}^{N} S_i \cdot \frac{v_i}{r_{iH}} e^{j(\omega t - k r_{iH} - \phi_i)} \quad (7)$$

In order to obtain sound pressure level the RMS value is needed. It is calculated as:

$$p_{H,rms} = \sqrt{\lim_{T\to\infty} \frac{1}{T} \int_0^T p_H^2 dt} = \sqrt{\frac{1}{2} \sum_{i=1}^{N} \sum_{k=1}^{N} B_{iH} B_{kH} \cos(\phi_{iH} - \phi_{kH})} \quad (8)$$

where

$$B_{iH} = \frac{\rho c k}{2\pi} \cdot \frac{v_i}{r_{iH}} \cdot S_i \quad (9)$$

$$\phi_{iH} - \phi_{kH} = k(r_{iH} - r_{kH}) + (\phi_i - \phi_k) \quad (10)$$

Finally, the sound pressure level is calculated as

$$L_p = 20 log_{10} \frac{p_{H,rms}}{p_0} \quad (11)$$

where

p_0 – reference sound pressure, $p_0 = 2 \cdot 10^{-5}$ $[Pa]$

A conversion from sound pressure level to corresponding sound power level was necessary. It was done with the formula:

$$L_W = \overline{L_p} + 10 log \frac{S_{meas}}{S_{ref}} \quad (12)$$

where

$\overline{L_p}$ – linear sound pressure level spatially averaged from a given prescribed contour, determined by the SPL program [dB]
S_{meas} – area of the measurement surface $[m^2]$
S_{ref} – reference area, $S_{ref} = 1$ $[m^2]$

The area of measurement surface was calculated as:

$$S_{meas} = l_m h_m \quad (13)$$

where
$l_m = a + 2x$ – length of measurement surface [m]
$h_m = b + 2x$ – height of the measurement surface [m]
a – transformer wall width [m]
b – transformer wall height [m]
x – distance from the principal radiating surface [m]

Equation 13 excludes the presence of the reflecting floor of the test bay. This can be justified by the fact that vibration results are independent from the presence of the floor, where acoustic results depend on its presence.

6. Results

Figure 4 presents radiation efficiency (sigma), A-weighted sound power level (LwA) and RMS average squared vibration velocity (v^2) plotted on a single chart, obtained from the method based on acoustic and vibration measurement. This kind of comparison help to analyze relationships between the three above-mentioned quantities.

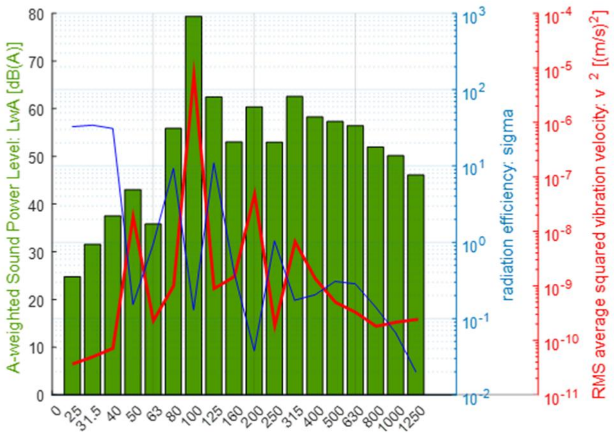
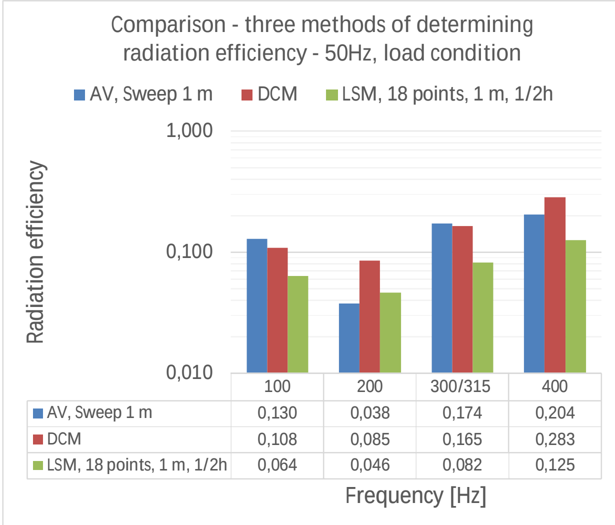


Figure 4. Radiation efficiency vs A-weighted sound power level vs RMS average squared vibration velocity.

Figure 4 reveals that the A-weighted sound power level for the 100 Hz component is more than 10 dB higher from the rest of bands. The same applies to RMS squared average vibration velocity, which is a few orders bigger from the results for other bands. Because of that, only the 100 Hz component is significant.

Figure 5 shows the comparison of the three investigated methods for determining radiation efficiency. It contains results in 1/3 octave bands for the method based on acoustic and vibration measurements (AV), and peak FFT values for the DCM and LSM methods (100, 200, 300 and 400 Hz bins). This way of comparison is valid, because differences between 1/3 octave and FFT results are negligible.



	100	200	300/315	400
AV, Sweep 1 m	0,130	0,038	0,174	0,204
DCM	0,108	0,085	0,165	0,283
LSM, 18 points, 1 m, 1/2h	0,064	0,046	0,082	0,125

Figure 5. Comparison of three methods of determining radiation efficiency – 50 Hz, load condition.

7. Conclusions

For the 100 Hz component at 50 Hz operating frequency of the transformer, the results of radiation efficiency for AV and DCM methods differ slightly (0,130 and 0,108 respectively, see Figure 5) while the third method (LSM) gives underestimated results (0,064). The difference may have its source in the direct (DCM) and the indirect (LSM) calculation of radiation efficiency. In the LSM, the sound pressure level is calculated first and then RE is calculated while in the DCM the vibration velocities themself give directly the RE value.

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