Sound & Vibration

Experimental and Numerical Study of the Key Non-Dimensional Geometrical Parameters on the Noise Level of Dry-Type Cast Resin Transformers

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Abstract: Dry-Type Cast Resin Distribution Transformers (CRT) is the second-generation of air-cooled distribution transformers where oil is replaced by resin for electrical insulation. CRT transformers may installed indoor adjacent to or near residential areas since they are clean and safe comparing to the conventional transformers. But, as it is obvious, noise discrepancy is intrinsically accompanied with all types of transformers and is inevitable for CRT transformers too. Minimization of noise level caused by such these transformers has biological and ergonomic importance. As it is known the core of transformers is the main source of the noise generation. In this paper, experimental and numerical investigation is implemented for a large number of fabricated CRT transformers in IT Co (Iran Transfo Company) to evaluate the effective geometrical parameters of the core on the overall sound level of transformers. Noise Level of each sample is measured according to criteria of IEC60651 and is reported in units of Decibel (dB). Numerical simulation is done using noncommercial version of ANSYS Workbench software to extract first six natural frequencies and mode shapes of CRT cores which is reported in units of Hz. Three novel non-dimensional variables for geometry of the transformer core are introduced. Both experimental and numerical results show approximately similar response to these variables. Correlation between natural frequencies and noise level is evaluated statistically. Pearson factor shows that there is a robust conjunction between first two natural frequencies and noise level of CRTs. Results show that noise level decreases as the two first natural frequencies increases and vice versa, noise level increases as the two natural frequencies of the core decreases. Finally the noise level decomposed to two parts.

Keywords: Experimental; FEM; mean noise level; CRT transformers; IEC60651

1 Introduction

Cast resin transformers (CRT) are the most attractive type of transformers in the field of distribution systems all over the world. These types of transformers are installed near residential areas since they are clean and safe in contrast to the common oil transformers. Despite of all benefits of these transformers, restriction of the noise in a standard level is a hot topic in debate. According to the literature the geometry of the core and magnetostrictions caused by the magnetic field are the most two important sources of noise in transformers.

Valkovic [1] has investigated the effects of overlap length of the core laminates and the assembly precision on the noise level in a single-phase model. It is reported that the noise level increases as the overlap length at the joints of the core is increases. Also, Valkovic and Rezic [2] have also examined the core losses and exciting power in a three phase transformer with step lap configuration core. Results showed that step lap cores have lower losses and exciting power in comparison with overlap ones. Literature survey showed that step lap configuration also has much better sound level characteristics. Laminated configuration of the core is the main cause of noise generation when magnetostriction happens. In addition, other parameters such as noise insulators, rubber dampers, and clamping force of the core may be the effective parameters on the overall noise level of the transformer. Snell [3] has used an experimental setup to evaluate the noise level of a step lap transformer according to the IEC60651 criteria. Due to the experimental results the choice of noise insulators between core and ground support and optimum clamping force are vital parameters for minimization of noise level. It is reported that cores with two laminated layers has higher noise level comparing to the cores with one laminated layers. Baehr [4] reported the effects of cutting shape of laminations and magnetic properties of them on the magnetic field characteristics and resulted noise level due to the magnetostriction forces. According to this work the uniform field is a way to minimize noise level. Weiser et al. [5] reported that the audible noise of transformer cores is depended on both magnetostriction and magnetic forces. Flux distribution highly influenced the Maxwell stress vectors especially at core corners which have the maximum dislocation normal to the lamination planes. Overlap regions has an attractive interlaminar force due to the normal components of induction field. According to their work multi-step-lap (MSL) configurations has lower audible noise in contrast to the single-step-lap (SSL) cores science even after dislocations are greater in MSL configuration but the lower harmonic distortions offsets the deficiencies. Inter laminar friction is also reported as another possible source of audible noise. Ilo et al. [6] reported the effects of overlap length, air gap length and length of overlap areas of adjacent core packages for both SSL and MSL configurations.

Distribution of magnetostriction at different regions of the core such as T-joints corners, and mid points of rolling and transverse direction of the core is reported in literature [7]. According to this work the magnetostriction at T-joints is greater than strain values at corners. Also it is reported that the magnetostriction in transverse direction is lower than rolling one. Krell et al. [8] have investigated the reasons of increased magnetostriction at T-joint regions of the transformer core. According to this paper rotational magnetization patterns at the T-joint region may be the cause of distinct increased magnetostriction. Magnetostriction stress tensor can be evaluated using finite element and Witczak and Weiser methods [5, 6, 10]. In this method, magnetostriction stress field can be evaluated from a known 2D magnetic field distribution. To minimize computational costs and time, some special 2D models is developed that could model the real three-dimensional structures of laminated thin sheets computationally [9]. Even after Witczak [10] has evaluated generated noise by magnetostriction as the dominant cause in no-load state but results show [11] that assumption of magnetostriction as the main cause of vibration increase in all situations is not sufficient. Ferromagnetic materials have both magnetic and elastic properties. The relation between these two properties is known as magnetostriction. According to the literature [12], there is different ways such as annealing that could be used to enhance magnetostriction characteristics of grain-oriented alloys of transformer cores.

In some other works two ways for noise controlling and reduction nominated passive and active methods recommended [13, 14]. In passive case some vibration absorbers can be used to reduce the mechanical vibrations amplitude. But this method could be useful at high frequencies which is useless for low working frequencies. Active noise controlling method uses a source of noise generation in an anti-phase to minimize or cancel the audible noise for both low and high operational frequencies [15]. Even after there are a large number of parameters that affect noise level of transformer but it is obvious that geometry of the transformer and structure of its core have a vital effect on the generated noise level. For instance laminated structure of the core has the most important role in noise generation. There are some efforts to model the core numerically considering its real laminated structure [16, 17]. According to these papers magnetostrictive strains which has the alternative frequency twice the power system supply and magnetic flux frequency is the main cause of noise generation. Also, as a new research work [18], the purpose of the paper [18], is to propose three imperialist competitive algorithm (ICA)-based models for predicting the blast-induced ground vibrations in Shur River dam region, Iran. In addition, according to reference [19], the magnetostriction damps the vibrations at some frequencies and increases them at some other ones. Recently, novel and applied research works have been done and analyzed about modeling and measurement of a tunable acoustoelastic system [20], and experimental and numerical investigation on the external aerodynamic noise of high-speed train [21]. Also, applied and different research works have been performed about test instrument for the automatic compliance check of cast resin insulated windings for power transformers [22], bushing failure in power transformers [23], and comparison of electrical parameters of oil-immersed and dry-type transformer using FEM [24].

All tests have been carried out at Iran Transfo Co. as the largest manufacturer of transformer types and the owner of the largest and most comprehensive laboratory of laboratory transformers in the Middle East. Also, good agreements were found between the obtained results and available real data with high accuracy. On the other hands, the validations of data with test samples have been measured with high precision in this paper. Estimation of noise in the transformers is one of the important problems. This presented method predicts this undesired noise before designing and manufacturing of transformers, and then solve this problem using changes in geometrical parameters (resulted in optimum noise amount). Therefore, in this paper, with the help of statistical data with experimental results, the formula is finally extracted. The amount of noise of the transformer is estimated with a maximum of 10% error.

In this paper, experimental and numerical investigation will implement to evaluate the effective geometrical parameters of the core on the overall sound level of transformers. Noise Level of each sample will measure according to criteria of IEC60651 and ANSYS Workbench 14 commercial software will be used to extract natural frequencies of the transformer core using FEM method for a 3D laminated core model (Standard International First Edition [Conference], IEC: 2001-05).

2 Experimental Test-Rig for Measurement

Test-rig, all experimental measurements, and all other considerations for noise evaluation are according to the IEC60651 criteria. Due to this standard, the fabricated transformer is located on a special stand in an appropriate acoustic room denominated acoustic chamber that is shown in Fig. 1.

Measurement points has one meter horizontal distance from transformer where are marked with white points on the stand as illustrated in Fig. 1. An appropriate sound-probe is implemented to record sound level near marked points with approximately one meter vertical distance from stand. Measurements are repeated for every point in two states which one of them is no-load state when transformer has no load at all and recorded sound level is only relative to the ambient noise. The other state is loaded one when the transformer is under electrical load and recorded sound level is the summation of both ambient and transformer noises together.

Equations (1, 2) may be used to evaluate mean noise level of transformer for both states- loaded and no-load states respectively-after recording the sound level for each point in each state. Then these two mean values should be subtracted from each other to give an approximate value of mean noise level of desired transformer.

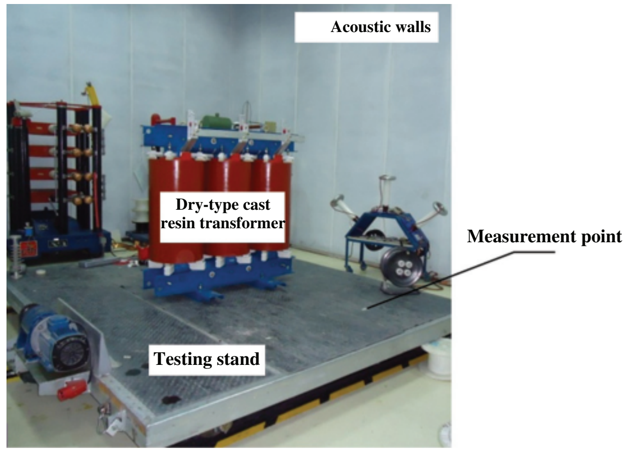


Figure 1: Test-rig for noise value evaluation due to IEC60651

$$\overline{LpA0} = 10\log\left(\frac{1}{N}\sum_{i=0}^{n} 10^{.2LpA0}\right) \quad (1)$$

$$\overline{LbgA} = 10\log\left(\frac{1}{M}\sum_{i=0}^{m} 10^{.2LbgA}\right) \quad (2)$$

The so-called noise test was implemented for eighteen different transformers with different core dimensions as tabulated in Tab. 1. The second column of this table shows the power of the transformers that are used in this study. Third column shows the measured and calculated mean noise level of every tested transformer. Main dimensions of the transformer core such as width of the core "l", overall height of the core "H", overall thickness of the core "T", maximum width of the core legs "P_{max}", minimum width of the core legs "P_{min}" where are illustrated in Fig. 2 may also be found in appropriate columns of this table.

Three novel non-dimensional geometrical parameters which are nominated HPR (Height to Pan Ratio), HBR (Height to Bore Ratio), and HTR (Height to Thickness Ratio) in this study are defined according to Eqs. (3–5). Using these values one can estimate the dimensions where mean noise level of the transformer may become minimum or maximum. These values can also be used to find dimensions where the first two natural frequencies of the transformer core are maximum or minimum. This is included in numerical analysis section of the present work.

$$HPR = H/L \quad (3)$$

$$HBR = H/p_{max} \quad (4)$$

$$HTR = H/T \quad (5)$$

As it is mentioned in abstract section of this paper, core of the transformers are the main source of noise generation in transformers. To trace the relation of the calculated mean noise level of the tested transformers to the dimensions of the core, the column graphs "HPR", "HBR", and "HTR" are plotted as it is shown in Fig. 3. These graphs could give an insight to the non-dimensional values of the geometry of the core that may minimize noise level. This knowledge could be very helpful to minimize the final overall noise of the

Table 1: Measured values of mean noise level

No.	Power (KVA)	Mean noise level (db)	L (mm)	H (mm)	T (mm)	P_{min} (mm)	P_{max} (mm)
1	200	41.3	1040	1060	158.8	80	170
2	400	44.3	1090	1380	177	80	190
3	400	43.9	1210	1150	187.6	90	200
4	500	51.9	1300	1310	192.2	90	200
5	500	46.8	1180	1360	190	90	200
6	630	46.9	1230	1410	183.2	90	200
7	800	40.73	1310	1400	209.8	110	220
8	1250	52.7	1520	1710	230.6	120	250
9	1250	63.07	1400	1670	214.4	110	230
10	1600	53.2	1530	1730	237.3	130	260
11	1600	48.9	1530	1930	228.9	130	260
12	2500	55.3	1830	1770	243.6	130	270
13	2800	49.4	1600	1700	271.4	150	300
14	3000	47.8	1640	1700	273.8	150	300

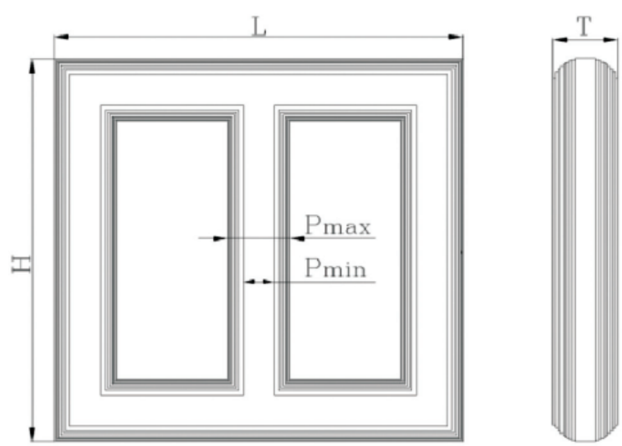
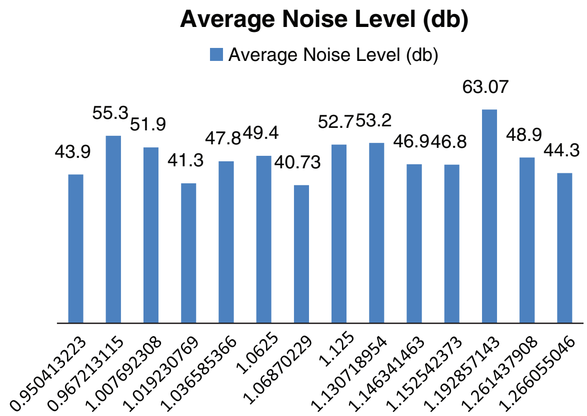


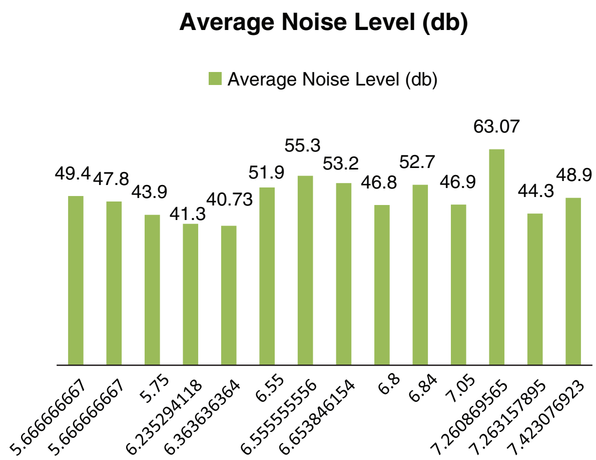
Figure 2: Main dimensions of the core

transformers prior to the manufacturing of them. In the other words, using these graphs the core dimensions of the transformers under construction may be changed considering other design criticisms in such a way that mean noise level fall between values as minimum as possible.

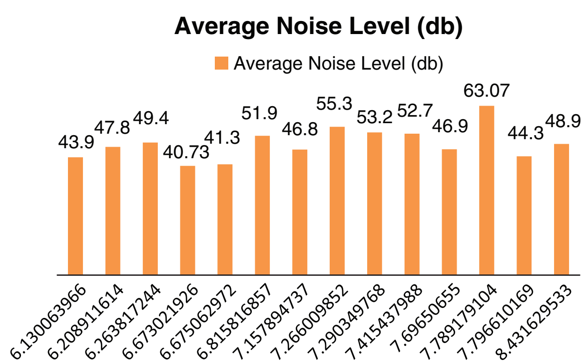
Even after experimental results and plotted column graphs in this study may be useful to find appropriate dimensions that could minimize overall noise of the final fabricated transforms prior to the manufacturing but this method is very expensive, time consuming and most of them the obtained results could only be expanded to cases that are located in limitations of the tested samples. On the other hand numerical simulations are less expensive and could be used to find a general solution. In this work we used modal simulation to find the



a-(HPR)



b-(HBR)



c-(HTR)

Figure 3: Mean noise level against (a) "HPR", (b) "HBR", and (c) "HTR"

relation between natural frequencies of the core of all tested transformer and their non-dimensional geometrical values "HPR", "HBR", and "HTR". Natural frequencies of the core are dependent to the material and geometry of the core similar to the noise level. As it will be shown there is a similarity between variations of computed natural frequencies and measured mean noise level of different tested transformers. To search for a correlation between natural frequencies of the transformer core and overall mean noise level of the transformer, the statistical Pearson factor will also be calculated.

3 Numerical Method

3.1 Geometry of the Model

Geometry of the model is depicted in Fig. 4. This model is 1/8-fraction of the 3-phase transformer core that its dimensions are given in Tab. 1. Four symmetry planes are highlighted with red color as illustrated in Fig. 5. The fixed area of the core which is pressed by the press-plates is shown with PP (Press-Plate) balloon in Fig. 5.

3.2 Meshing and Grid Independency

Rectangular hexahedral elements are used to mesh the model. To check the effects of grid size on the results, the mesh is refined three times and the total deformation on an arbitrary edge of the core middle

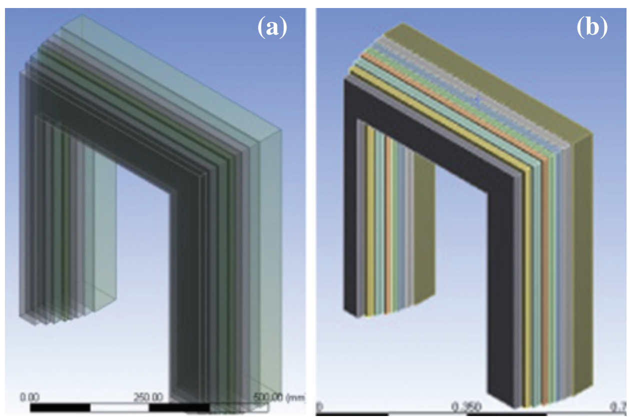


Figure 4: (a) The 1/8-fraction of the 3-phase transformer core, (b) model ready for simulation in ANSYS

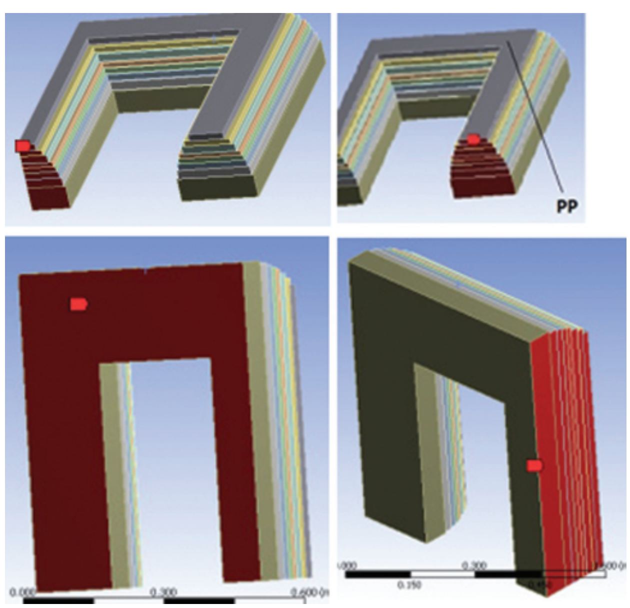


Figure 5: Illustration of symmetry planes

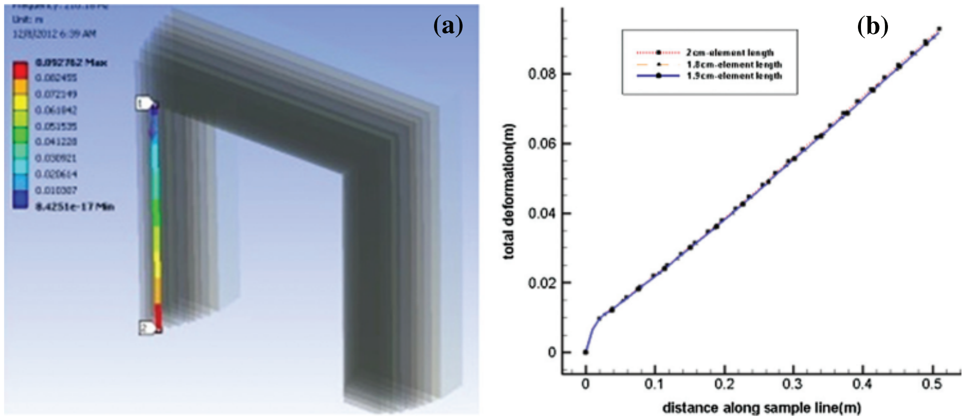


Figure 6: (a) Sample edge for deformation evaluation, (b) grid independency graph

leg is considered as a sample in each grid size which is highlighted in Fig. 6a. The extracted values of total deformation along the selected edge for each grid size are plotted as is shown in Fig. 6b. According to this graph the mesh with 2 cm and lower maximum size is good enough to be ensured of grid independency.

Meshing with elements in an appropriate maximum size range will give us the model like Fig. 7. Note that all laminates of the core are bonded together and there is no slip between layers.

Mesh parameters are as follow: Aspect ratio of final mesh "1.06–2.01", Jacobian ratio "1–1.04", Warping factor "zero", parallel deviation "0.02–1.48", maximum corner angle "90.02–103.17", orthogonally quality "98–100%", and Skewness "0–15%". All elements have good quality conditions in the range of 87–100% so the results are numerically validated.

3.3 Governing Equations

Modal analysis is done with calculation of the eigenvalues. Assuming linear elastic behaviors of the core material the Hook's law is applicable and dynamic equation of motion for FEM model is according to Eq. (6) as below.

$$[M]\left[\ddot{U}\right] + [C]\left[\dot{U}\right] + [K][U] = [F] \tag{6}$$

Where $[M]$ is mass matrix, $\left[\ddot{U}\right]$ acceleration vector, $[C]$ damping, $\left[\dot{U}\right]$ velocity vector, $[K]$ elasticity, and $[U]$ the displacement vector. For free vibration without damping, $[C]$ and $[F]$ is zero and Eq. (6) will simplify to Eq. (7).

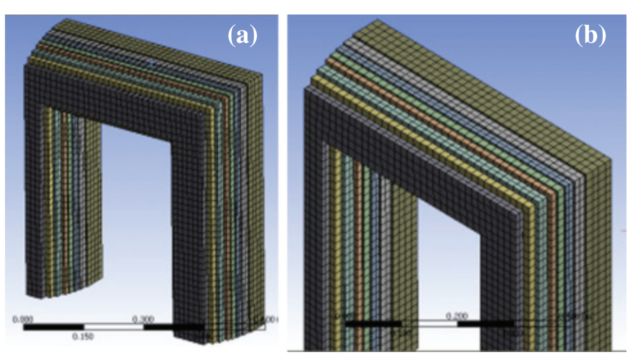


Figure 7: (a) Final grid that is used for simulation, (b) exaggerated view of generated mesh

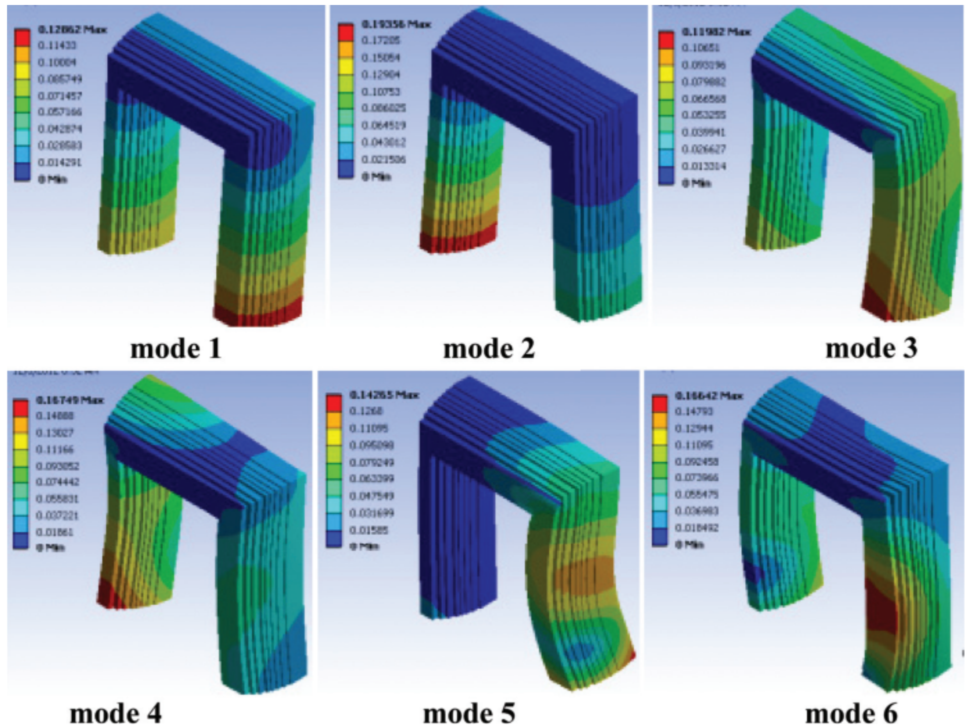


Figure 8: First six mode shape of vibration-case5

$$[M]\left[\ddot{U}\right] + [K][U] = [0] \tag{7}$$

In the case of free vibration, replace acceleration vector $\left[\ddot{U}\right]$ with $\lambda[U]$ and we have:

$$\lambda[U] + [K][U] = [0] \tag{8}$$

Solving this set of the linear equations will give eigenvalues.

4 Results and Discussion

Figure 8 shows the deformation contours of the core for six first mode shapes of case5 as a sample. In mode 1 and 2 the right and middle legs of the core will deform in a walking-like manner respectively. In mode 3 the core will bend relative to the yoke axis. Mode 4 and 5 show the bending of the middle and right legs of the core relative to the normal axis respectively. In the mode 6, a simultaneous opposite bending of the core legs relative to the normal axis in a scissors-like manner is observed. There is a similar behavior for all other cases. Values of six first natural frequencies are extracted for all cases that are reported in Tab. 2.

To search a correlation between natural frequencies of the transformer core and measured mean noise level of transformer, the statistical Pearson factor is calculated using SPSS software. Calculated Pearson factors between each natural frequency and mean noise level are according to Tab. 3.

Pearson factor between first natural frequency of the tested transformers and corresponding measured noise level is 0.968. This value is 0.634 between second frequency and noise. High Pearson factor shows that there is a robust correlation between first and approximately second natural frequency of the transformer core and mean noise level of the transformer. It seems that other frequencies have no

Table 2: Six first natural frequencies of all cases

No.	P (KVA)	Natural freq1 (Hz)	Natural freq2 (Hz)	Natural freq3 (Hz)	Natural freq4 (Hz)	Natural freq5 (Hz)	Natural freq6 (Hz)
1	200	269.74	439.18	1278.1	1663.5	2069.2	2345.3
2	400	167.6	289.77	959.8	1294.5	1536.8	1717.9
3	400	267.17	445.41	1200.2	1547.7	1891.9	2185.3
4	500	210.18	341.64	1026.8	1324.3	1694.4	1863.5
5	500	185.43	317.29	978.79	1305.6	1582.1	1774.8
6	630	177.61	289.93	982.84	1272.6	1536.1	1702.3
7	800	208.77	364.19	976.59	1281.6	1557.7	1738.2
8	1250	139.08	159.04	739.45	865.26	1158.6	1361.5
9	1250	149.08	270.34	806.64	1122.1	1244.6	1421.1
10	1600	163.73	262.58	802.66	1053.1	1224.8	1391.7
11	1600	138.36	200.57	726.77	940.97	1072.7	1211.5
12	2500	114.01	147.09	612.58	750.38	870.33	973.59
13	2800	183.47	317.62	828.05	1128.8	1204.4	1498.1
14	3000	189.4	316.55	815.26	1083.6	1269.6	1471.5

Table 3: Pearson factor between natural frequencies and measured mean noise level

	Noise (db) and freq.1 (Hz)	Noise (db) and freq.2 (Hz)	Noise (db) and freq.3 (Hz)	Noise (db) and freq.4 (Hz)	Noise (db) and freq.5 (Hz)	Noise (db) and freq6. (Hz)
Pearson factor	0.968	0.634	0.006	0.006	0.008	0.006

correlation with noise level. The first and second natural frequencies of the transformer core are plotted against non-dimensional values "HPR", "HBR", and "HTR" as illustrated in Fig. 9. Comparing these graphs with relative column graphs depicted in Fig. 3 it is deduced that whenever natural frequency of the transformer core falls, the mean noise level of the transformer rises and vice versa, whenever natural frequency rises, noise level falls. Lower natural frequencies are closer to the frequencies of probable exciting sources. One of the most important sources is the strain caused by magnetic field known as magnetostriction that has frequencies twice the frequency of the line- approximately 100 Hz.

Results show that prior to the fabrication of the transformer, the core dimensions could be changed in such a way that considering other electrical limitations, maximum natural frequency for the first mode shape of the transformer core is achieved. It is shown that numerical simulation shall help to minimize overall noise level of transformer in design phase prior to the fabrication. Noise histograms could also be used to forecast noise values in units of Decibel (dB) according to three recommended non-dimensional values. Correlation

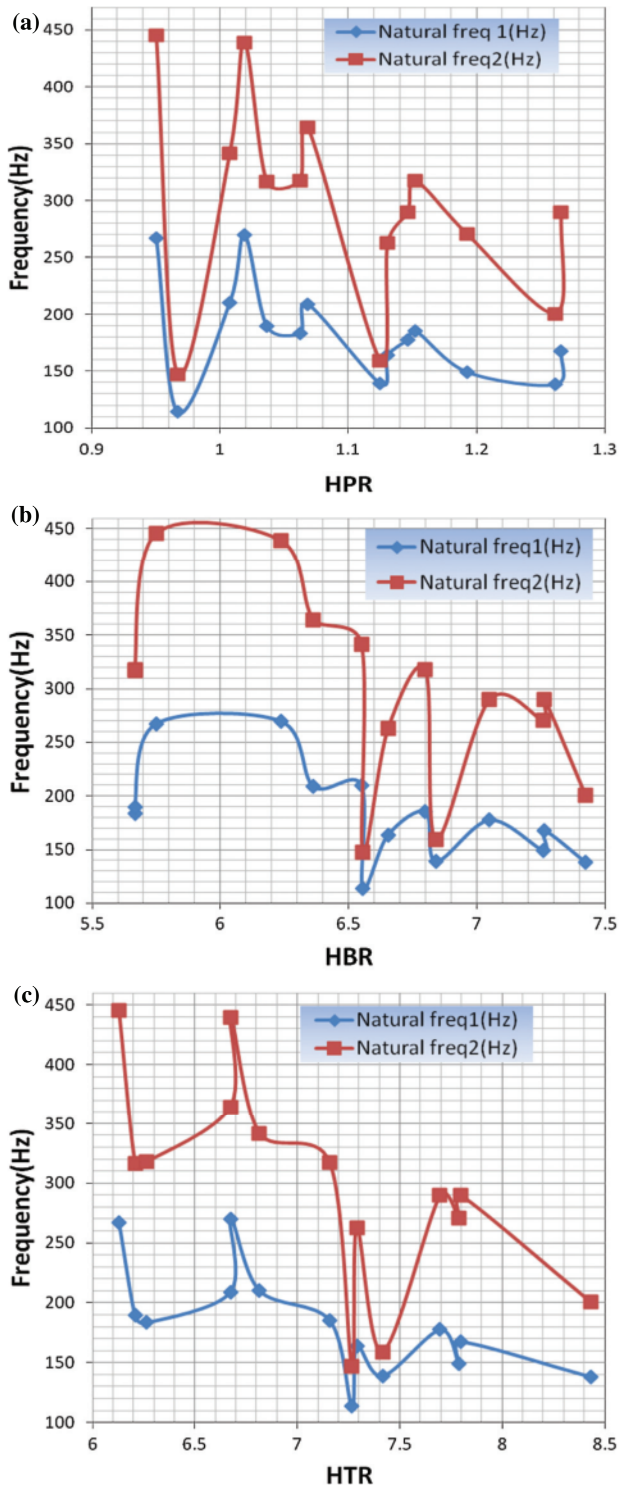


Figure 9: First and second natural frequencies of the transformer core against non-dimensional geometrical values (a) "HPR", (b) "HBR", (c) "HTR"

between numerical and experimental values to evaluate mean noise level of the transformers prior to fabrication in design phase, a correlation between the numerical and experimental values will be studied in this section in such a way that knowing dimensions of the core of the transformer and first natural frequency of the core as the main effective parameters, approximate value of the mean noise level could be forecasted.

To do so, there are some assumptions. First, it is assumed that the overall mean noise level of the transformer is the superposition of the noises caused by two known major sources. First source is the geometry of the core of the transformer. Dimensions of the core of the transformer may be designed in such a way that produces as minimum noise as possible. But there is a fact that the bios value of noise that seems to be dependent to the geometry of the core of the transformer could not be canceled completely but could be minimized.

On the other hand some part of the noise seems to be depended to the resonance of the core when the natural frequency of the core is near to the frequency of the magnetostriction frequency read twice the line frequency equal to 100 Hz. We denominated this frequency here as the critical frequency. We also assumed that in transformers with cores having first natural frequency far enough from critical frequency the overall noise is just affected by the geometrical dimensions of the core and the compartment of the resonance is negligible.

In this study, the first natural frequencies greater than 200 Hz are assumed to be far enough from critical frequency so the effects of resonance is negligible. Mean noise values for fourteen cases are measured numerically and their first natural frequencies are extracted numerically that are tabulated in Tab. 4. The cases with first natural frequencies greater than 200 Hz have approximately the lowest values of mean noise level (see Tab. 4).

We denominated frequencies greater than 200 Hz as safe frequencies and 200 Hz frequency itself as the threshold frequency in this work. As it is mentioned previously the effects of geometry on noise level could be considered using three non-dimensional values HBR, HTR, and HPR. In cases with safe natural frequencies the experimentally measured noise values could be plotted against these three non-dimensional values according to Figs. 10–12, respectively,

According to Fig. 10 noise in transformers with safe frequencies could be approximated by a first order polynomial that means there is a linear relation according to Eq. (9) between overall noise of transformer that is shown with λ_{noise} and non-dimensional geometrical parameter HBR.

$$\lambda_{noise} = -5.22(HBR) + 73.9 \quad (9)$$

Table 4: Numerical and experimental case studies show the first natural frequencies and average noise level respectively [Q2]

Experimental Case Number	First Natural Frequency	Average Noise Level (db)	Experimental Case Number	First Natural Frequency	Average Noise Level (db)
1	183.47	49.4	8	163.73	53.2
2	189.4	47.8	9	185.43	46.8
3	267.17	43.9	10	139.08	52.7
4	269.74	41.3	11	177.61	46.9
5	208.77	40.73	12	149.08	63.07
6	210.18	51.9	13	167.6	44.3
7	114.01	55.3	14	138.36	48.9

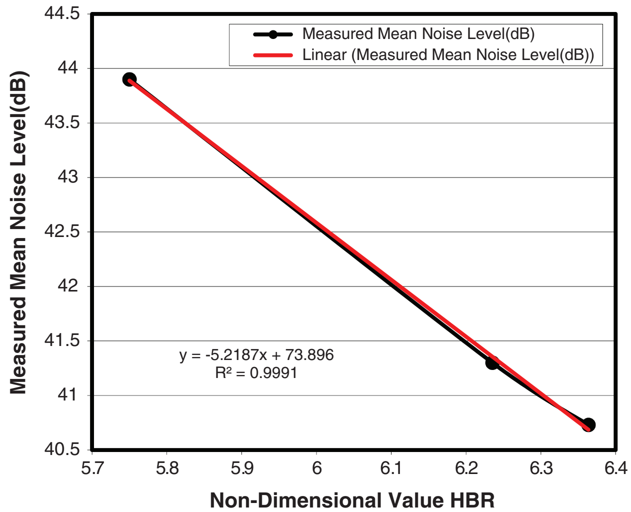


Figure 10: Measured mean noise level against non-dimensional value HBR

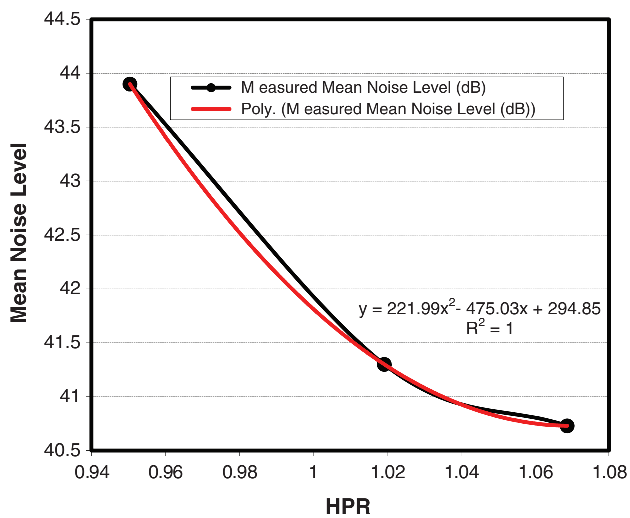


Figure 11: Measured mean noise level against non-dimensional value HPR

The graph illustrated in Fig. 11 shows the relation between HPR and measured mean noise level. As it could be deduced from this graph there is a second order polynomial relation according to Eq. (10) between HPR and measured mean noise level in transformers with cores having safe first natural frequency.

$$\lambda_{noise} = 222(HPR)^2 - 475.0(HPR) + 294.9 \quad (10)$$

The graph illustrated in Fig. 12 shows the relation between HTR and measured mean noise level. As it could be deduced from this graph there is an exponential relation according to Eq. (11) between HTR and measured mean noise level in transformers with cores having safe first natural frequency.

$$\lambda_{noise} = 187.0(HTR)^{-0.8} \quad (11)$$

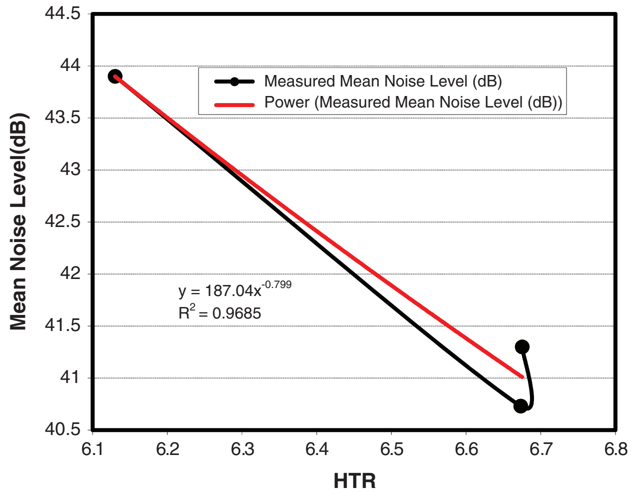


Figure 12: Measured mean noise level against non-dimensional value HTR

As it is mentioned we assumed that the noise level of transformers for cases with first natural frequencies below threshold frequency is the superposition of two parts a part from resonance and the other from geometry of the core. If we assume that Eqs. (9–11) also be valid for transformers below threshold frequency level, one can approximate the share of resonance in noise generation of the transformer subtracting the values caused by geometry from overall measured mean noise level. A new parameter that nominated frequency weight factor is also defined according to Eq. (12) to showing how far is the first natural frequency of the core's natural frequency from critical frequency,

$$\omega_f = \frac{200 - freq}{100} \tag{12}$$

Tables 5–7 show the share of noise caused by resonance after subtracting geometry share of the noise according to Eqs. (9–11) based on HBR, HPR, and HTR.

Table 5: Decomposition of measured mean noise level to two parts, share of noise caused by pure geometry and share of noise caused by pure resonance according to HBR

HBR	ω_f	Average Noise Level (db) Measured experimentally	Share of noise caused by Pure Geometry	Share of noise caused by pure resonance
5.67	0.1653	49.4	44.32	5.08
5.67	0.106	47.8	44.32	3.48
6.56	0.8599	55.3	39.68	15.62
6.65	0.3627	53.2	39.17	14.0
6.8	0.1457	46.8	38.41	8.4
6.84	0.6092	52.7	38.2	14.5
7.05	0.2239	46.9	37.1	9.8
7.26	0.5092	63.07	36.0	27.1
7.26	0.324	44.3	36.0	8.31

Table 6: Decomposition of measured mean noise level to two parts, share of noise caused by pure geometry and share of noise caused by pure resonance according to HPR

HPR	ω_f	Average Noise Level (db) Measured experimentally	Share of noise caused by Pure Geometry	Share of noise caused by pure resonance
0.97	0.1401	55.3	43.07	12.23
1.037	0.894	47.8	40.97	6.83
1.06	0.8347	49.4	40.74	8.66
1.13	0.3908	52.7	41.40	11.3
1.131	0.6373	53.2	41.55	11.66
1.147	0.7761	46.9	42.02	4.88
1.15	0.8543	46.8	42.24	4.561
1.193	0.4908	63.07	44.08	19.0
1.26	0.3836	48.9	48.87	0.035

Table 7: Decomposition of measured mean noise level to two parts, share of noise caused by pure geometry and share of noise caused by pure resonance according to HTR

HTR	ω_f	Average Noise Level (db) Measured experimentally	Share of noise caused by Pure Geometry	Share of noise caused by pure resonance
6.21	0.106	47.8	43.48	4.32
6.26	0.1653	49.4	43.18	6.22
7.16	0.1457	46.8	38.81	7.99
7.27	0.8599	55.3	38.35	16.95
7.29	0.3627	53.2	38.25	14.95
7.415	0.6092	52.7	37.73	14.97
7.7	0.2239	46.9	36.63	10.27
7.79	0.5092	63.07	36.28	26.8
7.8	0.324	44.3	36.25	8.05
8.43	0.6164	48.9	34.05	14.85

To extract an approximated relation between resonance share of noise and new defined parameter named frequency weight factor we could plot three graphs as below due to average noise level against frequency weight factor (ω_f) from Tabs. 5–7:

Share of overall noise due to resonance could be approximated with three different second order polynomials as it is plotted in Figs. 13–15. These equations could be summed with corresponding equations showing the share of noise due to non-dimensional geometrical parameters. Finally, three different Eqs. (13–15) will be deduced to evaluate overall noise level.

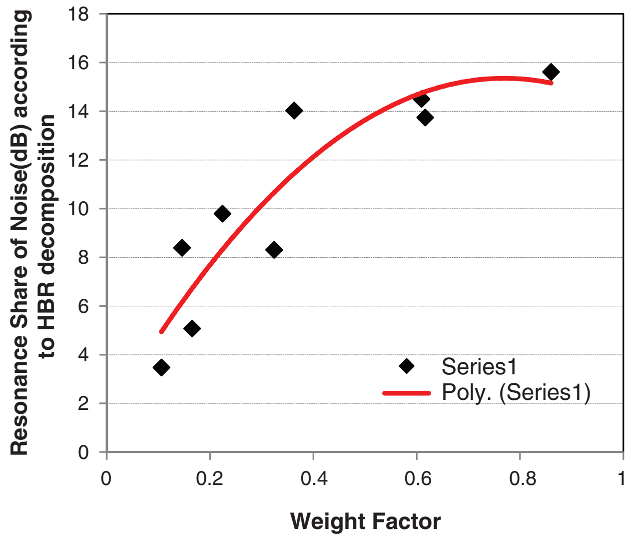


Figure 13: Resonance share of Noise according to HBR decomposition against frequency weight factor

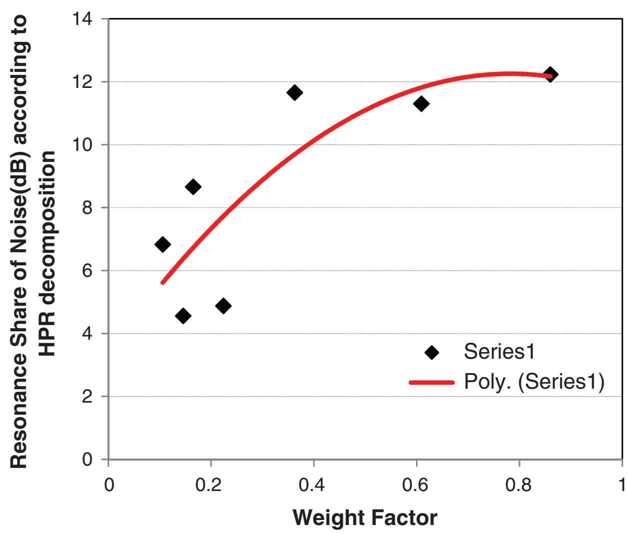


Figure 14: Resonance share of Noise according to HPR decomposition against weight factor

$$\lambda_{noise} = \{-5.22(HBR) + 73.9\} + \left\{-23.66\left(\omega_f\right)^2 + 36.4\left(\omega_f\right) + 1.351\right\} \tag{13}$$

$$\lambda_{noise} = \left\{222(HPR)^2 - 475.0(HPR) + 294.9\right\} + \left\{-14.5\left(\omega_f\right)^2 + 22.69\left(\omega_f\right) + 3.37\right\} \tag{14}$$

$$\lambda_{noise} = \left\{187.0(HTR)^{-0.8}\right\} + \left\{-20.7\left(\omega_f\right)^2 + 34.7\left(\omega_f\right) + 2.02\right\} \tag{15}$$

To search the accuracy of these equations the measured mean noise level is compared with corresponding computed values using Eqs. (13–15) where are plotted in Figs. 16–19 respectively. Fig. 16 (Graph) shows that overall noise values computed using Eq. (13) has –6.95% mean underestimation and

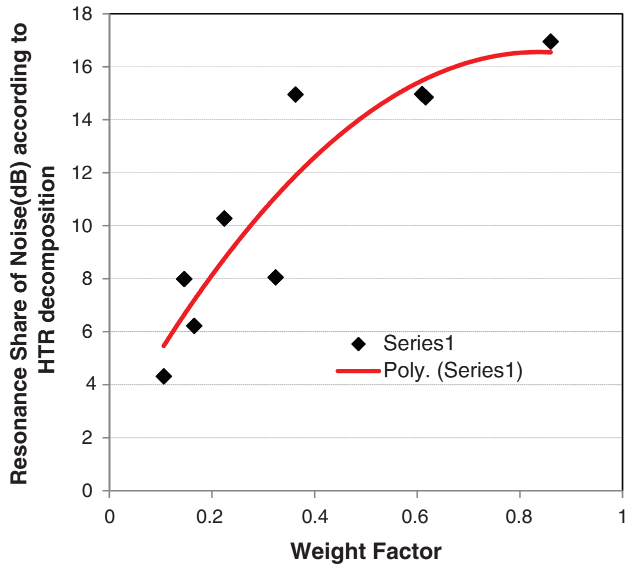


Figure 15: Resonance share of Noise according to HTR decomposition against weight factor

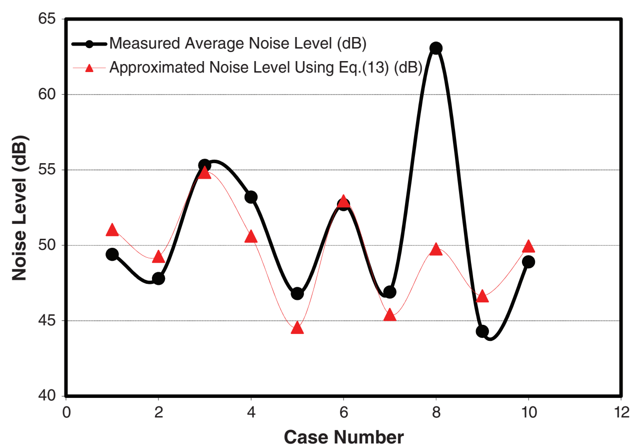


Figure 16: Comparison of measured average noise level with approximated noise level using Eq. (13)

2.87% mean overestimation comparing the experimental ones. Eq. (14) has –4.53% underestimation and 13.41% overestimation. Corresponding values are –6.5% and 2.71% for Eq. (15).

To make a unit equation to approximate mean noise level, three equations are summed together and is divided by 3 to make an averaged equation as Eq. (16) for cases with first natural frequency below threshold frequency and equation 16b for cases with first natural frequency in safe.

$$\begin{aligned}\lambda_{noise} = {} & \{-1.74(HBR)\} + \left\{74(HPR)^2 - 158.34(HPR)\right\} + \left\{62.34(HTR)^{-0.8}\right\} \\ & + \left\{-19.62\left(\omega_f\right)^2 + 31.263\left(\omega_f\right) + 125.18\right\}\end{aligned} \tag{16}$$

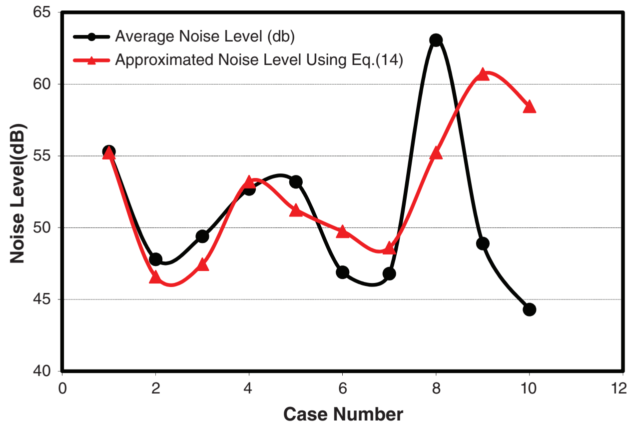


Figure 17: Comparison of measured average noise level with approximated noise level using Eq. (14)

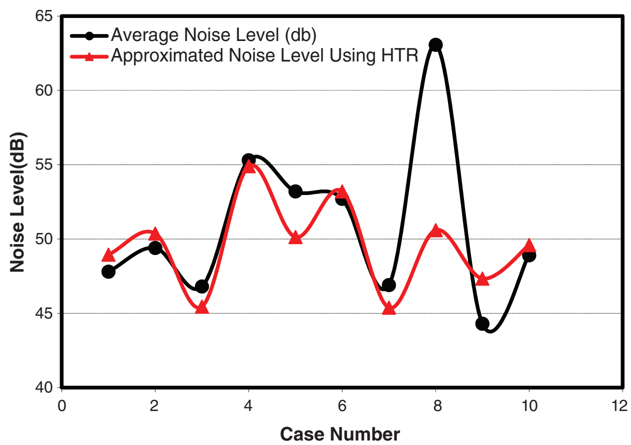


Figure 18: Comparison of measured average noise level with approximated noise level using Eq. (15)

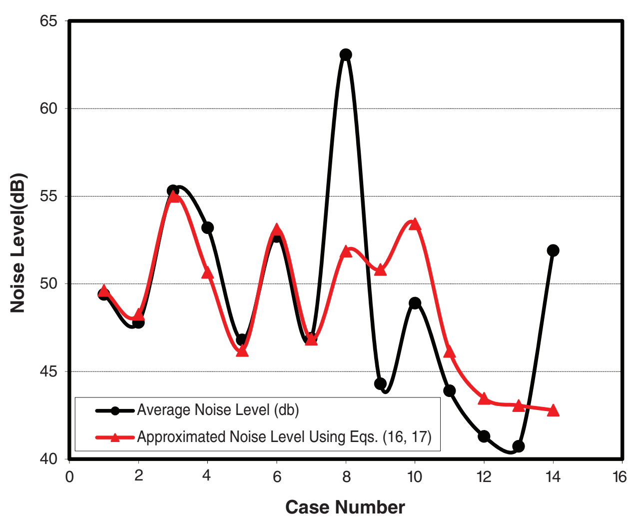


Figure 19: Comparison of measured average noise level and approximated noise level using Eqs. (16, 17)

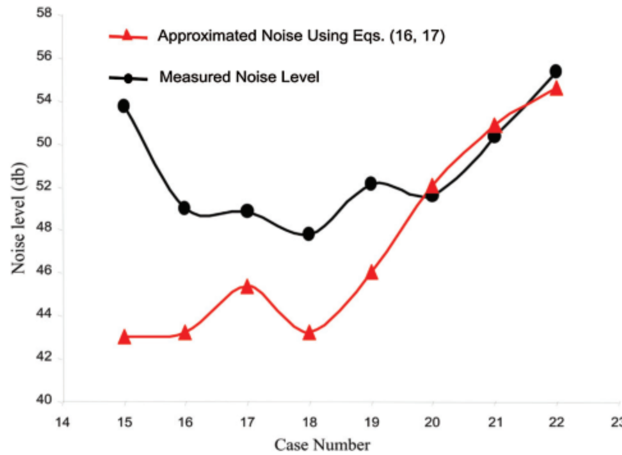


Figure 20: Comparison of measured mean noise level with approximated values for witness cases using Eqs. (16, 17)

Table 8: Specifications of witness cases

No.	Power (KVA)	Mean Noise Level (dB)	L	H	T	P_{min}	P_{max}	HPR	HBR	HTR
15	400	53.7	1150	1260	185	90	200	1.096	6.3	6.81
16	500	48.99	1210	1260	188	90	200	1.041	6.3	6.7
17	630	48.8	1370	1300	202	110	220	0.949	5.91	6.44
18	630	47.78	1260	1330	197	100	210	1.056	6.34	6.75
19	800	50.1	1320	1400	200	110	220	1.061	6.37	7
20	1000	49.6	1390	1490	215	110	230	1.072	6.48	6.93
21	1250	52.3	1530	1660	233	120	250	1.085	6.64	7.12
22	2000	55.3	1970	2030	298	150	300	1.03	6.77	6.8

First natural frequency<200 Hz

$$\lambda_{noise} = \{-1.74(HBR)\} + \left\{74(HPR)^2 - 158.34(HPR)\right\} + \left\{62.34(HTR)^{-0.8}\right\} + 125.18 \tag{17}$$

For natural frequencies $\geq$ 200 Hz

Finally, we implemented all the procedure for 8 other cases as the witness cases to test the correctness and precision of the proposed equation for overall noise level evaluation. Experimental tests are implemented to evaluate noise values and numerical simulation is used to evaluate first natural frequency. Fig. 20 and Tabs. 8–11 list the values.

Table 9: Measured mean noise level of witness case studies and approximated values using Eqs. (16, 17)

No.	First natural frequency	ω_f	Measured Mean Noise Level (dB)	approximated noise according to superposed equation (16, 17)	error
15	206.28	>200	53.7	43.01	−19.9141
16	211.8	>200	48.99	43.2	−11.8353
17	219.92	>200	48.8	45.35	−7.08091
18	199.39	0.0061	47.78	43.2	−9.58715
19	187.97	0.1203	50.1	46.04	−8.1069
20	170.09	0.2991	49.6	50.06	0.921936
21	147.94	0.5206	52.3	52.9	1.080008
22	127.79	0.7221	55.3	54.6	−1.25985

Table 10: Measurments

Overstimated	Underestimated
−7.29032	5.071474

Table 11: Measurments

Overstimation	Underestimation
1.000972	−9.63069

5 Conclusion

CRT transformers as the second-generation of air-cooled distribution transformers may be installed indoor adjacent to or near residential areas since they are clean and safe comparing to the conventional transformers. Since noise discrepancy is inevitable, minimization of the noise level has biological and ergonomic importance. As it is known the core of transformers is the main source of the noise generation. In this paper, experimental and numerical investigation was implemented for a large number of fabricated CRT transformers in Iran transfo Co. to evaluate the effective geometrical parameters of the core on the overall sound level of transformers. Noise Level of each sample was measured according to criteria of IEC60651 and was reported in units of Decibel (dB). To do so the fabricated transformers were located on a special stand in an acoustic chamber and using a special sound-probe both mean background noise and mean loaded transformer plus background noise were recorded in a specified distance from stand according to the standard. Finally, an approximate value of mean noise level of transformers was calculated subtracting these two measured values. Numerical simulation was done using ANSYS Workbench 14 commercial software to extract first six natural frequencies and mode shapes of CRT cores which was reported in units of Hz. 1/8-fraction of the 3-phase transformer core considering symmetries was modeled for numerical analysis. Rectangular hexahedral elements were used to mesh the model. The mesh was refined three times to ensure grid independency. All elements of implemented mesh have good quality conditions so the results are numerically validated. Assuming the Hook's law is applicable modal analysis was done with calculation of eigenvalues. Three novel non-dimensional variables for geometry of the transformer core were introduced. Both experimental and numerical results show that there is a similarity between variations of computed natural frequencies and measured mean noise level of different tested transformers against these variables.

To search a correlation between natural frequencies of the transformer core and measured overall mean noise level of transformer, the statistical Pearson factor was calculated using SPSS software. High Pearson factor showed that there is a robust correlation between first natural frequency of the transformer core and mean noise level of the transformer. It is deduced that whenever natural frequency of the transformer core falls, the mean noise level of the transformer rises and vice versa, whenever natural frequency rises, noise level falls.

Lower natural frequencies are closer to the frequencies of probable exciting sources. One of the most important sources is the strain caused by magnetic field known as magnetostriction that has frequencies twice the frequency of the line. Results showed that prior to the fabrication of the transformer, the core dimensions could be changed in such a way that considering other electrical limitations, maximum natural frequency for the first mode shape of the transformer core is achieved. It is shown that numerical simulation shall help to minimize overall noise level of transformer in design phase prior to the fabrication. Noise histograms could also be used to forecast noise values in units of Decibel (dB) according to three recommended non-dimensional values.

References

1. Valkovic, Z. (1996). Investigations of core noise levels using a dry-type transformer model. *Journal of Magnetism and Magnetic Materials, 160,* 205–206. DOI 10.1016/0304-8853(96)00170-9.
2. Valkovic, Z., Rezic, A. (1992). Improvement of transformer core magnetic properties using the step-lap design. *Journal of Magnetism and Magnetic Materials, 112(1–3),* 413–415. DOI 10.1016/0304-8853(92)91216-G.
3. Snell, D. (2008). Measurement of noise associated with model transformer cores. *Journal of Magnetism and Magnetic Materials, 320(20),* 535–538. DOI 10.1016/j.jmmm.2008.04.143.
4. Baehr, R. (1978). Investigation into flux distribution in variable shape transformer cores. *Journal of Magnetism and Magnetic Materials, 9(1–3),* 167–169. DOI 10.1016/0304-8853(78)90044-6.
5. Weiser, B., Hasenzagl, A., Booth, T., Pf'titzner, H. (1996). Mechanisms of noise generation of model transformer cores. *Journal of Magnetism and Magnetic Materials, 160,* 207–209. DOI 10.1016/0304-8853(96)00171-0.
6. Ilo, A., Weiser, B., Booth, T., Pfützner, H. (1996). Influence of geometric parameters on the magnetic properties of model transformer cores. *Journal of Magnetism and Magnetic Materials, 160,* 38–40. DOI 10.1016/0304-8853 (96)00099-6.
7. Shilyashki, G., Pfützner, H., Hofbauer, F., Sabic, D., Galabov, V. (2010). Magnetostriction distribution in a model transformer core. *Journal of Electrical Engineering, 61(7),* 130–132.
8. Krell, C., Baumgartinger, N., Krismanic, G., Leiss, E., Pfützner, H. (2000). Relevance of multidirectional magnetostriction for the noise generation of transformer cores. *Journal of Magnetism and Magnetic Materials, 215-216,* 634–636. DOI 10.1016/S0304-8853(00)00247-X.
9. Hihat, N., Napieralska-Juszczak, E., Lecointe, J.-P., Sykulski, J. K., Komeza, K. (2011). Equivalent permeability of step-lap joints of transformer cores: computational and experimental considerations. *IEEE Transactions on Magnetics, 47(1),* 244–251. DOI 10.1109/TMAG.2010.2089800.
10. Kubiak, W. (2006). Identification of magnetostriction vibrations in power transformers. *Zeszyty Naukowe. Elektryka/Politechnika Łódzka, z, 109,* 51–61.
11. Hilgert, T., Vandevelde, L., Melkebeek, J. (2006). *Vibrations in magnetic cores due to magnetic forces and magnetostriction (Ph.D. Symposium)*. Faculty of Engineering, Ghent University, Ghent, Belgium.

12. Chudakov, I. B., Cha, S. Y., Woo, J. S., Chang, S. K. (1998). Effect of magnetic annealing on magnetostriction of grain oriented electrical. *Journal of Magnetics, 3(1),* 15–20.
13. Ross, C. F. (1978). Experiments on the active control of transformer noise. *Journal of Sound and Vibration, 61(4),* 473–480. DOI 10.1016/0022-460X(78)90449-2.
14. Ilo, A., Pfützner, H., Nakata, T. (2000). Critical induction – a key quantity for the optimization of transformer core operation. *Journal of Magnetism and Magnetic Materials, 215-216,* 637–640. DOI 10.1016/S0304-8853 (00)00248-1.
15. Berge, T., Pettersen, O., Sorsdal, S. (1998). Active cancellation of transformer noise field measurements applied acoustics *Conference, Acoustics Research Center, ELAB-SINTEF, The Norwegian Institute of Technology. Norway 23,* 309–320.
16. Masti, R. S., Desmet, W., Heylen, W. (2004). On the influence of core laminations upon power transformer noise *Proceedings of ISMA,* 3851–3862.
17. Soltanmohammadi, M., Eslamian, A. (2012). The investigation of the effect of cast resin transformer's core on the natural mode shapes and vibration. *ISME (conference), Shiraz, ISME*.
18. Behzadafshar, K., Mohebbi, F., Soltani Tehrani, M., Hasanipanah, M., Tabrizi, O. (2018). Predicting the ground vibration induced by mine blasting using imperialist competitive algorithm. *Engineering Computations, 35(4),* 1774–1787. DOI 10.1108/EC-08-2017-0290.
19. Belahcen, A. (2004). *Magnetoelasticity, magnetic forces and magnetostriction in electrical machines (Doctoral thesis)*. Helsinki University of Technology, Laboratory of Electromechanics.
20. Deborah, F., Garrett, L., Bansal, D., Schultz, R., Brake, M., Shepherd, M. (2018). Modeling and measurement of a tunable acoustoelastic system. *Sound and Vibration, 52,* 12–17.
21. Jiang, S., Yang, S., Zhang, B., Wen, B. (2019). Experimental and numerical investigation on the external aerodynamic noise of high-speed train. *Sound and Vibration, 53(4),* 129–138.
22. Dolce, S., Fiorucci, E., Bucci, G., D'Innocenzo, F., Ciancetta, F., Di Pasquale, A. (2017). Test instrument for the automatic compliance check of cast resin insulated windings for power transformers. *Measurement, 100,* 50–61. DOI 10.1016/j.measurement.2016.12.039.
23. Arias Velásquez, R. M., Mejía Lara, J. V. (2018). Bushing failure in power transformers and the influence of moisture with the spectroscopy test. *Engineering Failure Analysis, 94,* 300–312. DOI 10.1016/j.engfailanal.2018.08.006.
24. Amin, U., Talib, A., Qureshi, S. A., Hossain, M. J., Ahmad, G. (2018). Comparison of electrical parameters of oil-immersed and dry-type transformer using finite element method. *World Academy of Science, Engineering and Technology International Journal of Energy and Power Engineering, 12(5),* 341–345.