On the influence of core laminations upon power transformer noise

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Abstract

Power transformers can be sources of disturbing and annoying acoustic noise. This paper is a first phase report of a wider framework of study that investigates the noise radiation characteristics of air-cooled power transformers. The dynamics of the transformer core structure plays a significant role in the noise generation process. The reported work focuses on the influence of lamination of the core block on its structural dynamic behaviour. The degree of lamination of a core and its boundary conditions have been found to have a strong influence on its resonant behaviour and the need for an accurate modelling of these physical details has been observed through a combined experimental – numerical study.

1. Transformer noise – an annoying disturbance

Power transformers are designed for the transmission and distribution of electrical power. Apart from satisfying this functional performance objective, the operation of a transformer happens to induce some annoying *acoustic radiation*.

The requirement for more electrical power associated with the growing density of population, especially in urban areas, has resulted in enhancing the supply capacity of local electrical substations by adding more transformers, or building new substations of high power ratings closer to the neighbourhoods. This may result in the inhabitants in the vicinity being exposed to increased, and often disturbing, noise levels.

Transformer acoustic noise is a *hum* characterised by spectral spikes at harmonics of the fundamental frequency (100 Hz /120 Hz) which is twice the line supply frequency. The transformer's low frequency tonal noise components are the major source of annoyance and intrusion, invoking noise complaints from the residents, [1, 2]. A growing awareness and concern about public health problems due to noise pollution has brought transformer substations under the purview of tough regulations on excessive noise emission. Therefore, the need for compliance to stricter noise control regulations requires the construction of transformers that are less noise-prone and the design of efficient passive/active control systems for on-site noise control measures. For this purpose, a proper understanding of the noise generation in a transformer and an accurate estimation of its radiation characteristics are necessary.

2. Noise sources and transmission paths in transformers

A transformer is a structural-acoustic system, by virtue of the dynamic interactions between its structural and fluid subsystems. A vibro-acoustic analysis of a transformer helps in investigating the vibrational and acoustic interactions between its components and their contributions in the noise generation mechanism and the resulting noise radiation into its outer surroundings. The work presented in this paper is part of a wider framework of study concerning the vibro-acoustic analysis of transformers (air-cooled) for predicting its noise radiation characteristics.

The primary source of acoustic noise generation in a transformer is the periodic mechanical deformation of the transformer core and the winding coils, under the influence of fluctuating electro-magnetic flux associated with these parts [1, 3, 4]. The physical phenomena associated with this tonal noise generation can be classified as follows:

- The material of a transformer core exhibits magnetostrictive properties. The vibration of the core is due to its magnetostrictive strain varying at twice the frequency of the alternating magnetic flux. The frequencies of the magnetic flux is equal to the power system supply frequency and its harmonics.
- When there are residual gaps between laminations of the core, the periodic magneto-motive force may cause the core laminations to strike against each other and produce noise. Also, the periodic mutual forces between the current-carrying coil windings can induce vibrations if there are any loose turns of the coil.

Some of the other sources of noise in a transformer, such as the cooling fans and the pumps, are considered to be negligible contributors to the far-field noise.

During a transformer’s operation, the vibrations from its core and windings get transmitted to the transformer tank surface through air-borne transmission i.e. the air surrounding the core. Also, the vibrations can reach the tank by structure-borne transmission at points where the mounting of the core structure is attached to the tank. The vibrating tank surface eventually radiates noise into the exterior air. Complex vibro-acoustic interactions are involved during this process. Figure 1 gives a schematic view of the noise generation and transmission in a transformer.

The following three stages of vibro-acoustic modelling procedure will be adopted in the evaluation of noise radiation characteristics of the transformer associated with the present work.

1. Vibrations of the core due to the exciting magnetic force will be determined. Rigid mounting conditions of the core will be considered.
2. Reaction forces at the mounting joints of the core frame will be derived from the previous step and be used to calculate the structure-borne vibrations of the remaining structural components. The velocity information derived from the vibrations of the core and windings will be used to describe the boundary condition at the interface of the transformer fluid (air) domain with the core structure to evaluate the air-borne transmission.
3. The outer surface vibrations of the transformer tank serve as input for a boundary element model for the far-field noise emission calculation.

3. Dynamic behaviour of the transformer core

3.1. Introduction

The structural components of a transformer such as the core, windings, transformer mounting, tank, etc., are continuous systems with an infinite number of natural frequencies of vibration. The core has been identified as a major source of noise. When a core’s natural frequency coincides with an excitation frequency, the core can resonate with large deformations if not properly designed. The core vibrations when transmitted through the fluid and/or structure-borne could induce also resonance phenomena in other components that are not direct sources of noise. This enhanced vibrational energy when transmitted to the tank surface could result in an amplified noise radiation.

Although the core has to meet the transformer's electrical system requirements, it is important that the core structure does not resonate at any of its excitation frequencies that are related to the power system frequency and its harmonics. A core structure is a complicated stack of Si-Fe alloy laminations clamped together at suitable points. The laminated design of a core is indispensable in order to reduce the eddy current losses and hence lower the heating of the core structure. Clamping is essential to hold together the laminations. The clamping arrangement also influences the dynamic behaviour of a core. Accurate mechanical modelling of the core structure is important for a proper description of its dynamic behaviour. The work presented in this paper deals with some of the modelling aspects of a dynamic transformer core model.

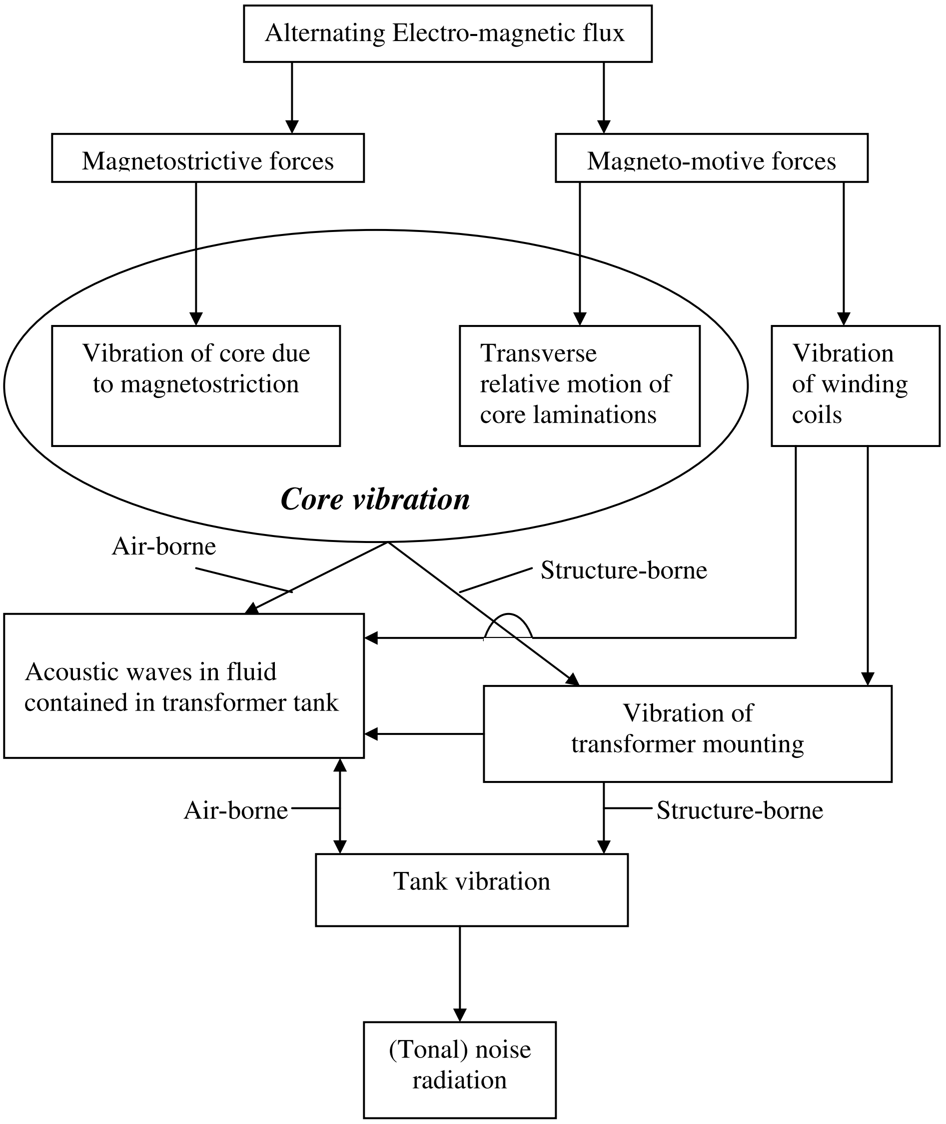


Figure 1: A schematic view of noise generation and transmission in a power transformer.

3.2. Typical construction of a transformer core

A photo of a typical core of a transformer (rating 400 kVA) is shown in Figure 2. The yokes and the legs of the core have stepped cross-sectional areas formed by a stacked arrangement of thin laminations. Each layer of lamination has an average thickness of 0.28mm. Considering its physical details, a lamination on its own is a flimsy layer. These laminations, although clamped at certain points, still can have a freedom for relative in-plane motions over their remaining interface areas. As laminations may not have good matching flat surfaces and as they are not clamped together over an entire surface area, residual gaps between the laminations are unavoidable. Magneto-motive forces acting across these air gaps could set relative transverse motions between the laminations. Also, with clamped constraint points in place, deformation due to magnetostriction could set additional bending of the lamination plates. Therefore, it seems interesting to study in detail the effect of laminations on the flexibility of the core structure. A preliminary study of these effects is presented in the following sections.

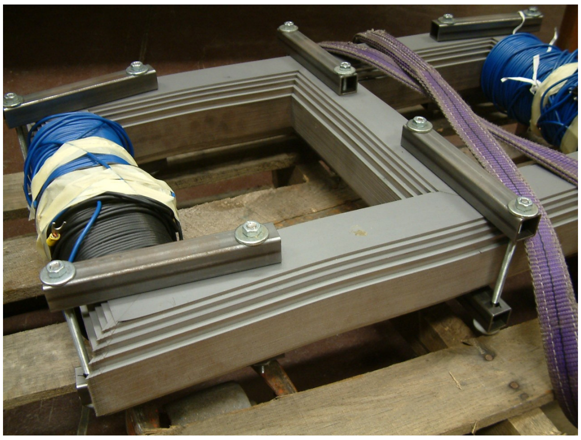


Figure 2: A photo of a typical transformer core.

3.3. Numerical modelling of the core

3.3.1 Introduction

Finite element analysis is used in this study to understand the dynamics of the laminated core structure. The FE model representation of the core is such that reliable results can be obtained yet keeping the size of the problem small, in order to reach a balance between accuracy and the computational cost of the analysis process.

The rectangular core block is modelled for three degrees of lamination refinement.

1. A single solid block (no lamination)
2. An assembly of several blocks
3. A fully laminated core

The natural frequencies and mode shapes are obtained from a finite element (FE) analysis of the core. The commercial finite element software MSC Nastran® 2004 is used for the analysis. In all three case studies, free boundary conditions of the core are considered.

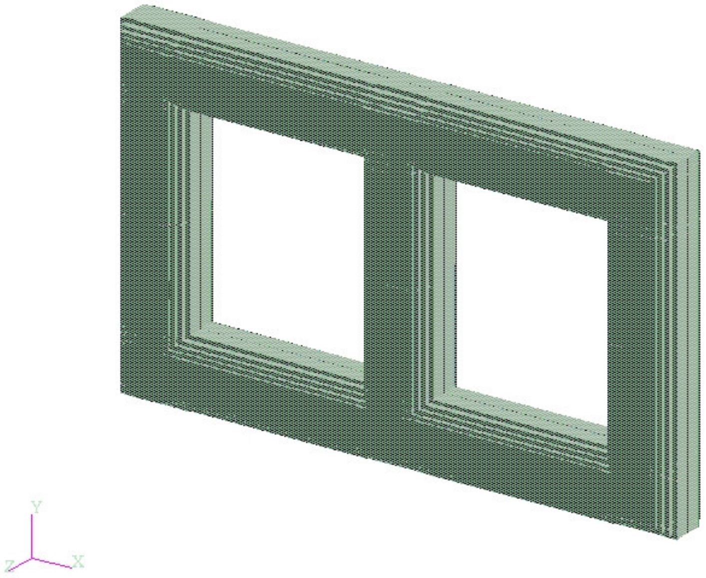


Figure 3: Transformer core

<u>Properties of the core material used in the analysis</u>

Young's modulus: 2.1E+11 N/m^2

Density: 7650 kg/m^3

Poisson's ratio: 0.3

3.3.2. Three levels of lamination

Case 1: A single solid block

The entire core is considered as a single entity block as shown in Figure 3. For the analysis purpose, only a top half of the block is used. Suitable symmetric and anti-symmetric boundary conditions are considered along the plane of symmetry. The FE model is composed of HEX8 solid elements and has a total of 217,710 dofs in the model. Table 1 gives a list of the first natural frequencies obtained for the core.

No.	Frequency (Hz)
1.	1.541535E+03
2.	1.759291E+03
3.	2.693693E+03
4.	3.293237E+03
5.	3.621515E+03
6.	4.773287E+03
7.	5.026964E+03
8.	5.041570E+03
9.	5.572688E+03

Table 1: The first resonance frequencies (Hz) of the solid block

Case 2: An assembly of several blocks

In this case, the core is considered to be a stacked arrangement of 9 separate blocks, with interfaces between the blocks at the transitions between contour steps of the core's profile (see Figure 4). The core blocks are considered to be bolted together at six separate points as shown in Figure 5. Except for these bolted positions, a sliding interface surface (parallel to x-y plane) is modelled between each pair of blocks. There are no gaps between the blocks i.e. in a sliding surface region, both the nodes of a coincident-node-pair have the same displacement along z-axis (normal to the surface). There are no frictional forces between the blocks. For modelling the bolting, consider a pair of blocks. At the interface of the blocks, the displacement for example in x direction is identical for a coincident-node-pair lying on the bolt-axis. Similar conditions are imposed for displacements in y and z directions. The complete core is used in the FE model. The model is composed of HEX8 solid elements and has a total of 586,335 dofs. Table 2 gives a list of the first natural frequencies of the core.

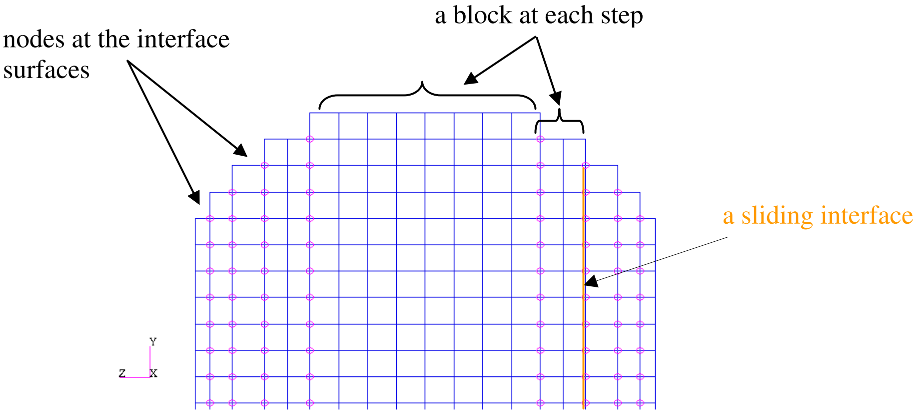


Figure 4: A side view of a portion of the core having a set of blocks. The FE model shows the coincident pairs of nodes at the interface surfaces between the blocks.

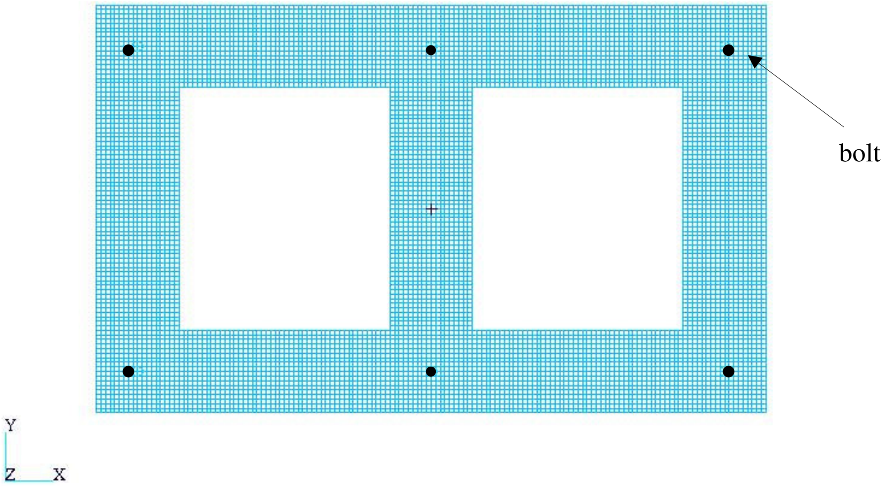


Figure 5: A front view of the FE model of the complete core with six bolts.

No.	Frequency (Hz)
1.	7.715997E+02
2.	9.246251E+02
3.	1.773283E+03
4.	2.484734E+03
5.	2.513804E+03
6.	2.583557E+03
7.	2.843469E+03
8.	2.899457E+03
9.	3.151394E+03

Table 2: The first resonance frequencies (Hz) of the assembly of blocks

Case 3: Fully laminated core

Each of the blocks of the model in Case 2 is further sliced into laminations, so that the core model corresponds to the actual laminated core of the transformer. The original transformer core is a stacked arrangement of 300 laminations. Each lamination is of an average thickness of 0.28mm. In order to have a reduced size of the FE model, only a portion of the core is considered. By virtue of the symmetry of the complete core, only a 1/8th portion of the core (Figure 6) is considered. Figure 7 shows a portion of the laminated core FE model. Appropriate symmetric and anti-asymmetric boundary conditions are applied along the planes of symmetry. Again, core laminations are bolted together, now at two locations in this model. The bolts are at the same positions as that of the corresponding bolts in the Case 2 model. Except for the bolted positions, sliding interface surfaces (parallel to x-y plane) are modelled between each pair of laminations. On such a sliding surface region, both the nodes of a coincident-node-pair have the same displacement along z-axis (normal to the surface). There are no frictional forces between the laminations. The model is composed of HEX8 solid elements and has a total of 1,766,400 dofs. Table 3 gives a list of the first natural frequencies of the core. Figure 8 shows the mode shapes for some of the resonance frequencies of the core. The computational time for each test took an average of 4.5 hours on a Linux workstation (3 GHz single processor, 1GB RAM).

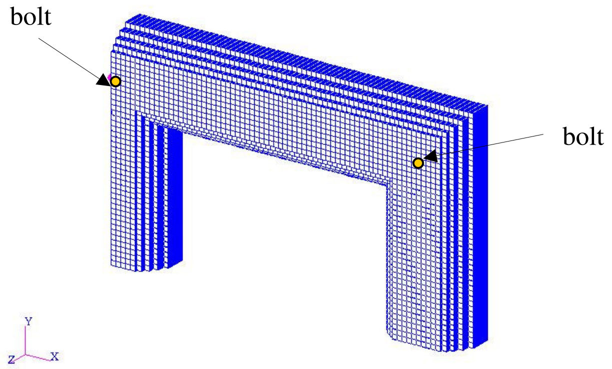


Figure 6: An FE model of a 1/8th portion of the core.

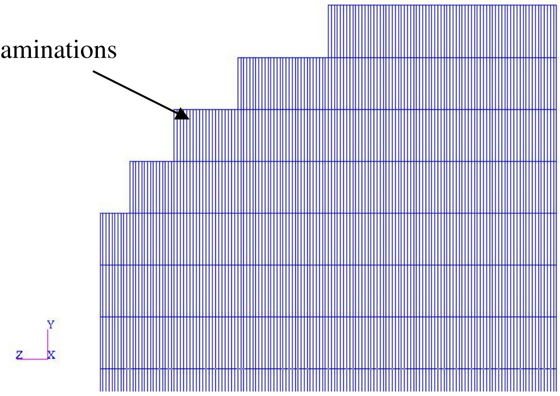


Figure 7: A portion of the FE model showing thin laminations of the core.

No.	Frequency (Hz)
1.	1.310731E+01
2.	1.322237E+01
3.	2.101505E+01
4.	3.772055E+01
5.	3.850163E+01
6.	4.421560E+01
7.	4.913927E+01
8.	5.125762E+01
9.	5.239173E+01

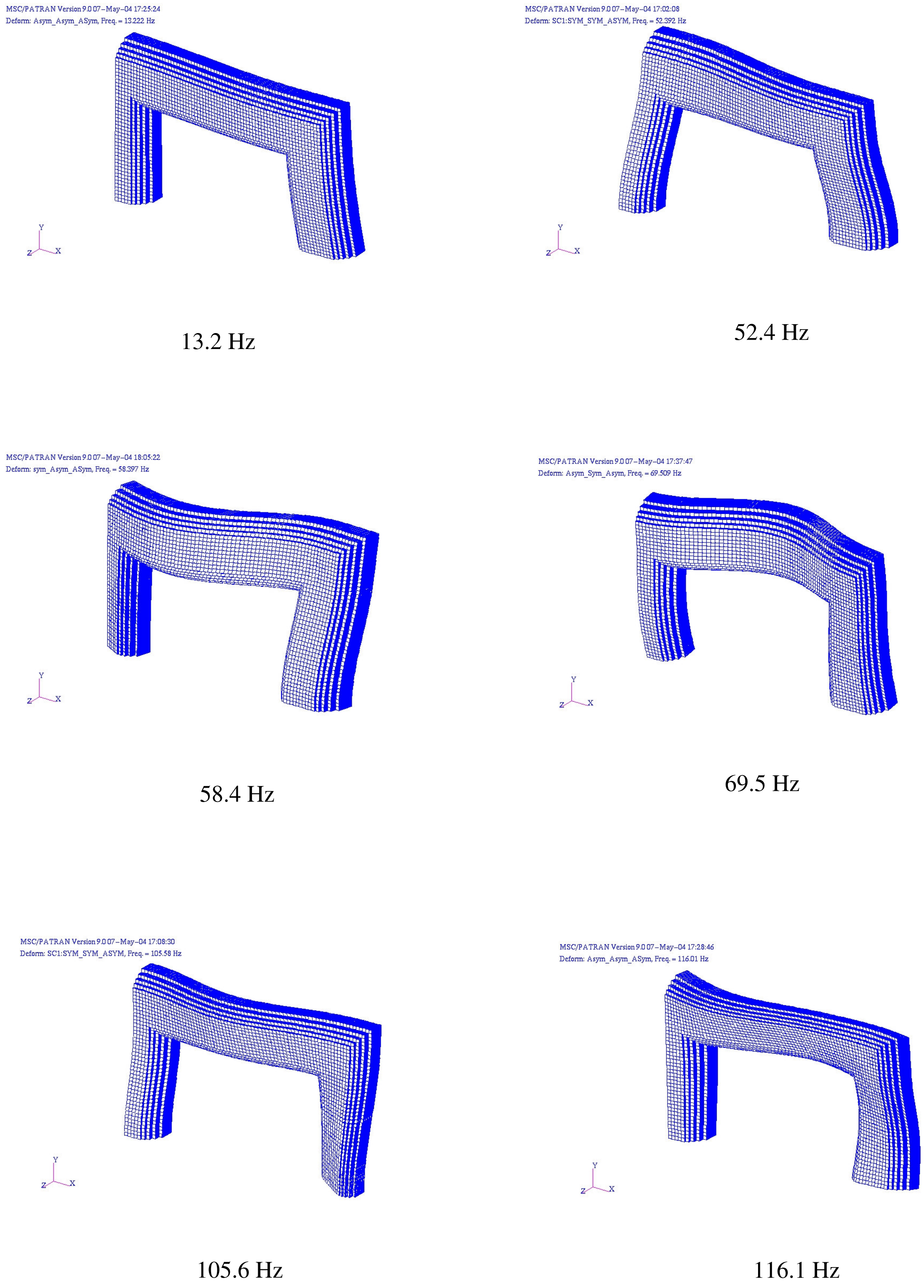
Table 3: The first resonance frequencies (Hz)

3.4. Experimental analysis

Table 4 lists the first frequencies obtained experimentally for the fully laminated transformer core with free boundary condition. The laminations were held together with the help of clamps symmetrically located at six positions (see Figure 2).

No.	Frequency (Hz)
1.	33.259365
2.	35.829113
3.	42.904289
4.	48.278542
5.	68.129242
6.	85.274178

Table 4: The first resonance frequencies (Hz)



13.2 Hz

52.4 Hz

58.4 Hz

69.5 Hz

105.6 Hz

116.1 Hz

Figure 8: Mode shapes for some of the resonance frequencies. A 1/8th portion of the core is shown.

3.5. Discussion of the results

The lamination of the core block into 9 separate blocks (Case 2) and restricting the clamping pressure points to a small number result in a significant lowering of its fundamental frequency by almost half i.e. from 1541.5 Hz to 771.6 Hz. Further laminating the core into 300 layers (Case 3) resulted in a 120-fold decrease in its fundamental frequency i.e. from 1541.5 Hz to 13.1 Hz. A closer spacing between the resonance frequencies is also observed when increasing the flexibility of the core through lamination. This might enhance clustering of more resonance frequencies in the vicinity of the excitation frequencies. With an increase in lamination of the core block, the resisting shear forces at the interfaces between sliding surfaces are eliminated and result in a decrease in the overall stiffness of the core. From the nature of influence of lamination on the dynamics of the core, as evident from the results in this study, it seems imperative to have a detailed geometrical modelling of the laminated core and its clamping arrangement.

It is obvious that the size of the FE model increases with the number of laminations. Going from Case 2 from Case 3, there was a significant increase in the size of the model. However, taking advantage of the symmetry of the core has made it convenient to handle by splitting one large problem into several smaller size problems.

The numerical results (natural frequencies in Table 2) for the first six modes of the fully laminated core are somewhat lower than the corresponding experimental results (in Table 4). These differences can be attributed to some of the following reasons:

(a) During the experiment, the clamping of laminations extends over a much wider area than considered in the numerical study (bolting along six bolt-axes only) and therefore causing a higher stiffening effect upon the core.

(b) The actual material properties of the core have not been measured. Therefore, only representative values of the properties were taken from literature.

Despite these differences, the order of magnitude of experimental and numerical results are comparable. This indicates that in general a detailed modelling approach is needed and that a fully laminated description is mandatory.

4. Conclusions and future research

The lamination of a transformer core and its clamping arrangement has a strong influence on the structural dynamics of the core. The vibration behaviour of the core structure has a significant role in its dynamic interaction with the surrounding fluid, the core mounting and various other parts connected to it, so that it has eventually an influence on the overall noise generation process. Therefore during vibro-acoustic modelling of a transformer, it is imperative to include a proper physical representation of the laminations of the core and its clamping arrangement.

Further research will look into the vibro-acoustic modelling and analysis to understand the dynamic interactions between the structural components and the air cavity of the transformer. This takes into account both structure-borne and air-borne vibrations eventually leading to the exterior radiation of noise from the tank surface.

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References

[1] P. Saha, *Power transformer noise – Generation, propogation and control – A review*, ASME publication - presentation at The Winter Annual Meeting, November 15-20, 1981, pp. 1-12.

[2] Kurt Brungardt, Jim Vierengel, Karen Weismann, *Active structural acoustic control of noise from power transformers*, Proceedings – National conference on noise control engineering, v2, 1997, pp.173-182.

[3] Arthur W. Kelly, *Measurement of spacecraft power transformer acoustic noise*, IEEE Transactions on Magnetics, Vol. 26, No.1, January 1990, pp. 281-289.

[4] Menno van der Veen, Francisco de Leon, Brian Gladstone, Valeriu Tatu, *Measuring acoustic noise emitted by power transformers*, AES 109th Convention, Los Angeles, September 2000, pp. 22-25.