RESEARCH ON MAGNETOMECHANICAL COUPLING RELATION IN AMORPHOUS METAL CORE TRANSFORMERS

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Abstract - The magnetostrictive force is a major cause of noise and vibration from a transformer. Especially, the magnetostrictive force of an amorphous steel core transformer is higher than that of a silicon steel core transformer. In order to accurately calculate and evaluate the noise and vibration of a transformer, it is necessary to fully examine such factors as deformation, displacement, vibration and magneto-mechanical force. In this paper a generalized mathematical model was set up with the above factors taken into consideration. The mathematical model was then developed on a single-phase amorphous steel core transformer with a capacity of 3,3kVA-220V/115V to result in the degrees of deformation and vibration in cases with or without clamped iron for magnetic legs and yokes. At the same time, these results were evaluated and compared with experimental ones, which helps determine a reasonable clamping force to minimize the noise and vibration of the amorphous steel core transformer.

Key words - transformer; amorphous; vibration; audible noise; magnetostriction; magnetomechanical.

1. Introduction

Amorphous magnetic steel (AMS) has been widely used in the fabrication of the magnetic core of transformers thanks to its very low losses. Compared to the traditional grain-oriented electrical steel, no load loss is decreased to about 1/5 of silicon steel's [1].

The amorphous alloy is a non-crystal substance (amorphous state) created by super fast cooling liquids metal from high temperature. Because there is no time forcrystal formation or arrangement, the energy loss (hyste-resis loss) is small when the flux of magnetic induction passes through the iron core. In addition, eddy current loss is decreased because the thickness is approximately 0.03 mm, which is about 1/10 compared to silicon steel.

Amorphous magnetic steel is very sensitive to the effects of temperature, deformation or the external magnetic field. This special material has also a large magnetostrictive coefficient (20µm/m) which causes large vibration and large displacement in the core of the transformer compared to the traditional steel core [2], [3].

Because of its energy efficient characteristics, amorphous magnetic steel core transformers are widely used in a distribution power system. When these distribution trans-formers are usually placed in a residential area, the noise problem caused by magnetostriction received lots of research interest. In [4], the authors have used the adaptive active control of amorphous alloy core transformers in order to reduce noises. In [5], the authors have presented the results of the numerical computing of electrical machine vibrations caused by Lorentz, Maxwell and magnetostriction forces without any detailed analytic model.

In [6], the authors have calculated the vibration of magnetic cores of power transformers due to magnetostriction based upon the coupling between the magnetic field and the mechanical deformation. Mechanical displacements also have been measured. However, audible noises and its related sources have not been investigated.

In the most recent paper [7], the authors have investigated the audible noises in three-phase three-leg transformers with different amorphous-cored structures. The results indicate that amorphous-cored transformer with a rectangular core has higher vibration intensities, a toroidal core should have lower core vibrations and audible noises than the counterparts.

In this paper, the authors have developped a generalised model for both mechanical and magnetic aspect. Thanks to this model, mechanical deformation, displacement and audible noises are linked together. Furthermore, their contribution to the total noise of the transformer is quantified. The mechanical parts such as clamping shackle at yoke and core limb and their influences on the audible noise have been measured. The optimal clamping force at each precise position has been pointed out.

2. Mathematical model

The causes of vibrations inside the steel core of transformers are created by magnetostrictive force. This is concretized by means of the diagram shown in Figure 1.

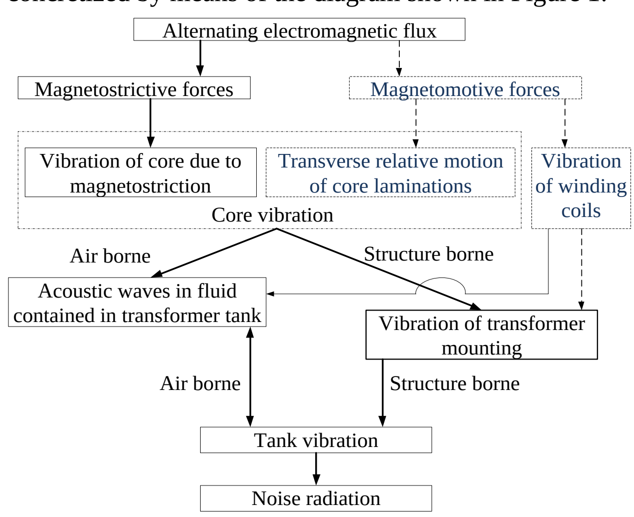

Figure 1. *The noise vibration in transformers [8]*

Based on [9], [10], [11], we have a substitute equivalent diagram which is equivalent to mixture electromechanical systems of the single-phase transformer as follows:

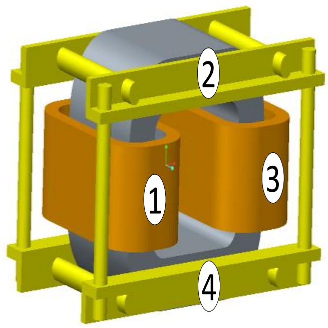

Figure 2. *The structure of survey transformer*

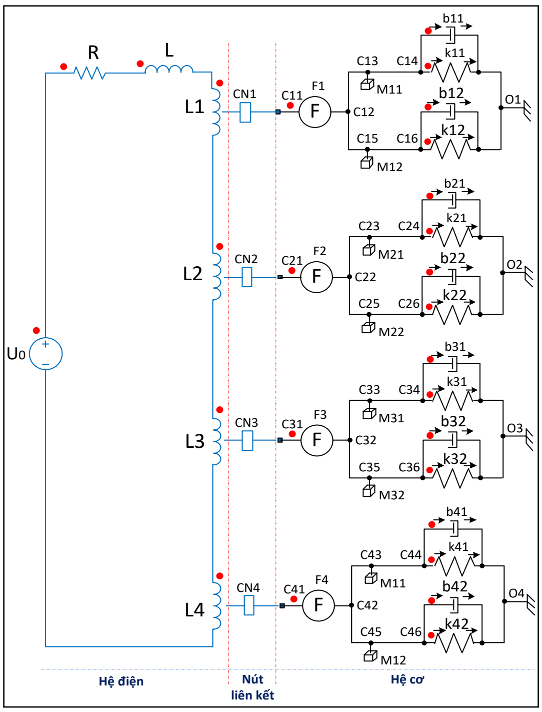

Figure 3. *The substitute equivalent diagram of transformers in mixture Magnetomechanical systems*

Table 1. *Symbols*

Name	Physical Description	unit
U_0	Max. voltage at high-voltage side	V
R	Resistors of the high-voltage coil	Ω
L	Inductance of the high-voltage coil	H
L_i	Inductance components when considering the magnetostrictive phenomenon effected to magnetic-leg and yoke in turns as Figure 2.	H
F_i	Mechanic-magnetic force (including magnetostrictive and magnetic force)	N
M_{ij}	The mass of the leg, yoke and iron clamps.	Kg
b_{ij}	Damper factor (Viscosity)	N.s/m
K_{ij}	Spring constant	N/m
ξ	Electromotive induction	V
$\mu = \mu_r\mu_0$	Absolute permeability factor	T.m/A
B	Magnetic induction	T
S	Deformation (caused by an external magnetic field)	µm/m
s^H	Elasticity strain factor (depend on H)	m^2/N
D	Magnetostrictive constant	m/A
L	Lenght of magnetic circuit	m
A	Cross section of steel-core	$[m^2]$
N	Winding turns number of high-voltage	turn
V	Velocity of the displacement	m/s

General Calculation Formula:

$$\begin{cases} \xi = \dfrac{\mu\lambda ANV}{l} \\ F = \lambda AB \end{cases} \quad (1)$$

$$\begin{cases} B = \mu H + \mu\lambda S \\ \lambda = \dfrac{d}{\mu s^H} \end{cases} \quad (2)$$

Reviewing the link point CN1, we have:

$$\begin{cases} V_1 = \dfrac{1}{m_{11}}\int F_{M11}dt = \dfrac{1}{b_{11}}F_{b_{11}} = \dfrac{1}{K_{11}}\dfrac{dF_{K_{11}}}{dt} \\ = \dfrac{1}{m_{12}}\int F_{M12}dt = \dfrac{1}{b_{12}}F_{b_{12}} = \dfrac{1}{K_{12}}\dfrac{dF_{K_{12}}}{dt} \\ F_1 = F_{M_{11}} + F_{K_{11}} + F_{b_{11}} + F_{M_{12}} + F_{K12} + F_{b12} \\ F_{01} = F_{K12} + F_{b12} + F_{K11} + F_{b11} \end{cases} \quad (3)$$

With $X_1 = \int V_1 dt$ the above equation has been rewritten:

$$\begin{cases} F_1 = (m_{11}+m_{12})\dfrac{d^2X_1}{dt^2} + (b_{11}+b_{12})\dfrac{dX_1}{dt} + (K_{11}+K_{12})X_1 \\ F_{01} = F_1 - (m_{11}+m_{12})\dfrac{d^2X_1}{dt^2} \\ X_1 = \int V_1 dt \end{cases} \quad (4)$$

With the same above way for the remaining points, we have the equations of the electromechanical mixture as follows:

$$\begin{cases} U_0\cos(2f\pi t) = iR_2 + L\dfrac{di}{dt} + \xi_{L1} + \xi_{L2} + \xi_{L3} + \xi_{L4} \\ \mu\dfrac{iN}{l_{mt}} = B \\ L\dfrac{di}{dt} = NA\dfrac{dB}{dt} \\ F_1 = (m_{11}+m_{12})\dfrac{d^2X_1}{dt} + (b_{11}+b_{12})\dfrac{dX_1}{dt} + (K_{11}+K_{12})X_1 \\ F_{01} = F_1 - (m_{11}+m_{12})\dfrac{d^2X_1}{dt} \\ F_2 = (m_{21}+m_{22})\dfrac{d^2X_2}{dt} + (b_{21}+b_{22})\dfrac{dX_2}{dt} + (K_{21}+K_{22})X_2 \\ F_{02} = F_2 - (m_{21}+m_{22})\dfrac{d^2X_2}{dt} \end{cases}$$

$$\begin{cases} F_3 = (m_{31}+m_{32})\dfrac{d^2X_2}{dt} + (b_{31}+b_{32})\dfrac{dX_3}{dt} + (K_{31}+K_{32})X_3 \\ F_{03} = F_3 - (m_{31}+m_{32})\dfrac{dV_3}{dt} \\ F_4 = (m_{41}+m_{42})\dfrac{d^2X_4}{dt} + (b_{41}+b_{42})\dfrac{dX_4}{dt} + (K_{41}+K_{42})X_4 \\ F_{04} = F_4 - (m_{41}+m_{42})\dfrac{d^2X_4}{dt} \\ X_1 = \int V_1 dt;\quad X_2 = \int V_2 dt;\quad X_3 = \int V_3 dt;\quad X_4 = \int V_4 dt; \\ \xi_{L1} = \dfrac{\mu\lambda A_1 N V_1}{l_1};\ \xi_{L2} = \dfrac{\mu\lambda A_2 N V_2}{l_2}; \\ \xi_{L3} = \dfrac{\mu\lambda A_3 N V_3}{l_3};\ \xi_{L4} = \dfrac{\mu\lambda A_4 N V_4}{l_4} \\ F_1 = \lambda A_1 B;\quad F_2 = \lambda A_2 B;\quad F_3 = \lambda A_3 B;\quad F_4 = \lambda A_4 B \end{cases} \qquad (5)$$

Handling the above differential-equation with the Runge-Kutta method (ODE45) we find out: magnetic induction B (T), current intencity I (A), magnetomechanical force F (N) and the displacement x(μm), deformation s(μm/m), acceleration a(m/s^2) on magnetic-leg and yoke of the transformer.

3. Modeling and Experiments

3.1. Modeling of the mechanical stress and displacement of the transformer

2605SA1 50Hz Material, magnetic field intensity H(A/m) and Magnetic induction B (Tesla) are shown in Figure 4; Young's elastic modulus of material E=120(GPa); Poisson-ratio ν=0,28; Vacuum permeability factor μ_0=4πx10^{-7}(T.m/A); Saturation magnetostriction λ_s=27(μm/m).

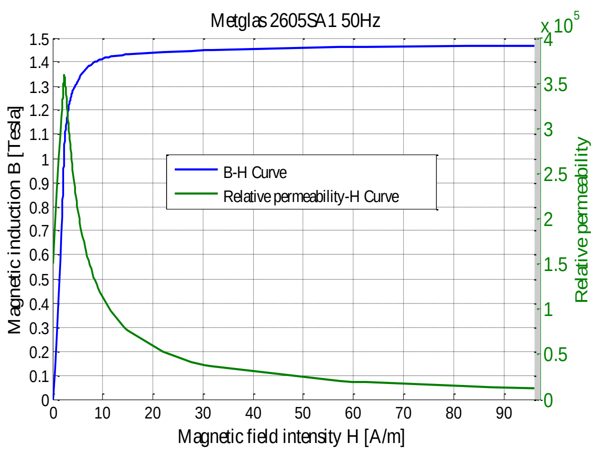

Figure 4. *Magnetization curve and relative permeability factor of the amorphous materials codes 2605 SA1 50Hz, Hitachi Metals, USA has been applied to the transformer core*

Table 2. *Basic electrical parameters and dimension of the transformer*

Item	Parameters	Value
1	No. of Phase	1
2	Frequency(Hz)	50
3	Power (kVA)	3,3
4	Voltage HV/LV(V)	220/115
5	No. of windings HV/LV(turn)	155/81
6	Thickness of core BD (m)	0,045
7	Width of core D(m)	0,142
8	Height of window H(m)	0,168
9	Width of window W(m)	0,06
10	Cross-section of core(m^2)	0,00639

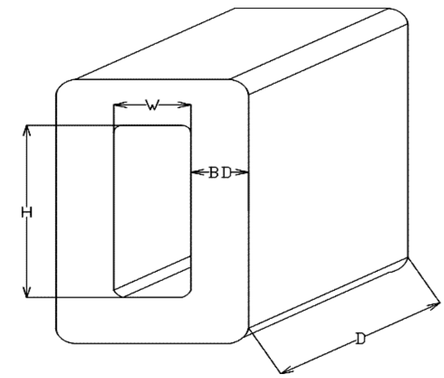

Figure 5. *Dimension of the surveyed transformer*

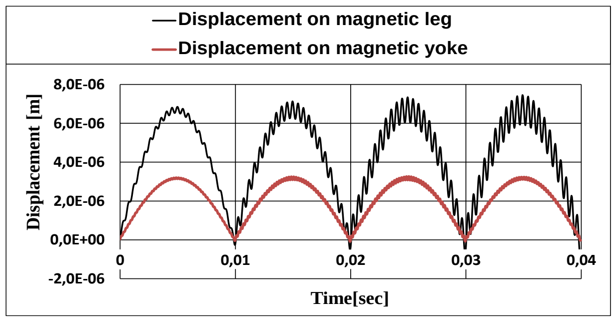

Figure 6. *The displacement on magnetic-leg and yoke without iron-clamping.*

Figure 6 shows an average length of yoke (105mm) and leg (213mm) then the displacement on magnetic leg and yoke is $x_{Yoke\ max}$ = 3,15μm < $x_{Leg\ max}$ = 6,84 μm.

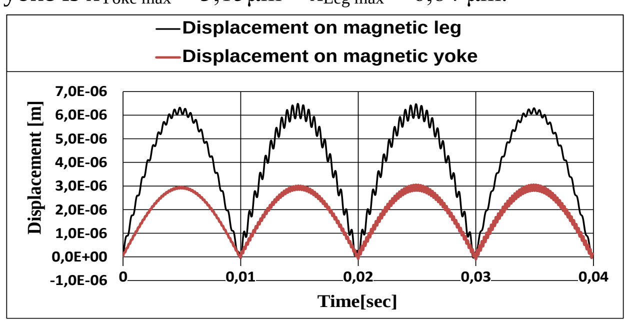

Figure 7. *Ddisplacement of position on magnetic leg & yoke with iron-clamping*

Based on Figure 7, when iron clamping is applied to fix magnetic-leg and yoke tightly, then $x_{Yoke\ max}$ = 2,9μm < $x_{Leg\ max}$ = 6,16 μm. Thus when the magnetic-leg and yoke are fixed tightly, the displacement shall be reduced 10% than no tightly fixed case. It is suitable with Figure 1, when the magneticleg and yoke are fixed tightly, then the transverse relative motion of core laminations shall be reduced.

Figure 8 shows the deformation of core without iron-clamping S_{kkmax} = 11μm and the deformation of core when applied iron-clamping S_{ckmax} = 10,3μm, this reduction is

6,36%. However, when compared with the result of the study [6], the displacement and deformation of the amorphous steel core is higher, which means that the vibration noise level in the amorphous steel cores would be higher than that of thd silicon steel core.

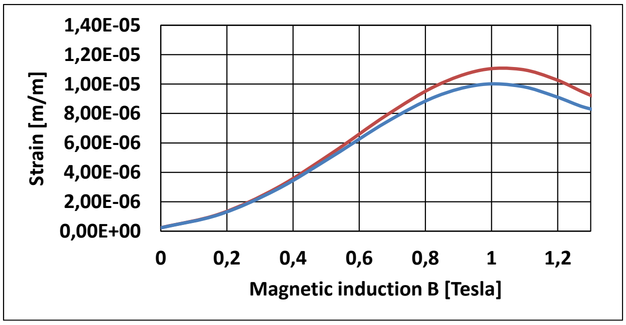

Figure 8. *The deformation of core with and without clamping*

From Figure 9 and Figure 10, we recognize that the max.vibration level when the magnetic leg and yoke have not fixed tightly is 2,302m/s^2, and when the magnetic-leg and yoke have fixed tightly is 1,963m/s^2, this vibration shall be reduced by 0,339 m/s^2 (14,72%).

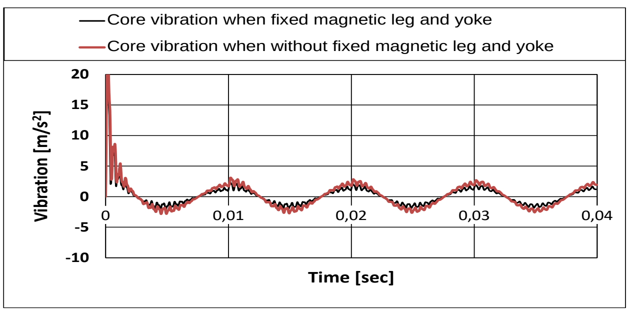

Figure 9. *Vibration level in steel core*

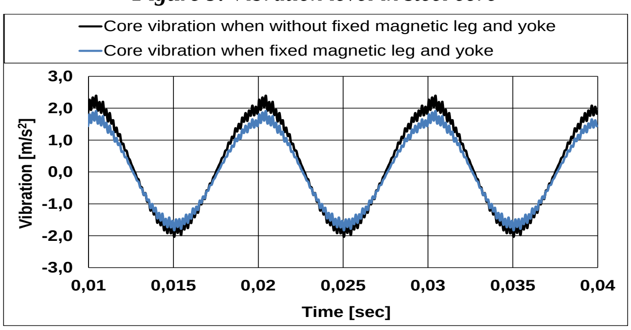

Figure 10. *Vibration level in steel core in a stabilized state*

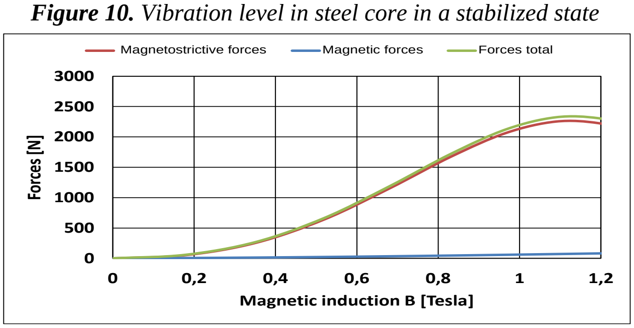

Figure 11. *The magneto-mechanical force in the steel-core of the transformer*

Basing on Figure 11, we have recognized that the magnetic force (which is created by the transverse relative motion of core laminations) is very small 100N, while the magnetostrictive force is very strong - approximately 2500N. It is over twenty five times of the magnetic force. Therefore all of the deformations, displacements and vibration noises inside the amorphous steel core are mainly created by the magnetostrictive force. Besides that, the amorphous steel has a saturation magnetostrictive factor so big (>20µm/m). Thus we can affirm that the amorphous steel core transformer has a vibration noise higher than that of the the silicon-steel core transformer.

3.2. Experiments

Similar to the results of the mathematical model, the experimental measurement results also have shown that if the magnetic leg and yoke have been clamped through by torque 4-5 N.m, then their vibration level is the smallest (Figure 13). When the magnetic leg and yoke have not been clamped, the vibration level of the steel core is the highest (Figure 12). The value of a_{maxkk} =3m/s^2 and a_{maxck} =2,3m/s^2, the vibration level has reduced by about 23,33%. So when the magnetic leg and yoke have been clamped tightly, the transverse relative motion of core laminations shall be reduced and also the vibration of coil (which has been created by the magnetic force) shall be reduced much more.

a_{maxkk} [m/s^2]: Range of vibration level in case the magnetic leg and yoke have not been fixed.

a_{maxck} [m/s^2]: Range of vibration level in case the magnetic leg and yoke have been fixed.

a_{kk} [m/s^2]: The effective vibration level in case the magnetic leg and yoke have not been fixed.

a_{ck} [m/s^2]: The effective vibration level in case the magnetic leg and yoke have been fixed.

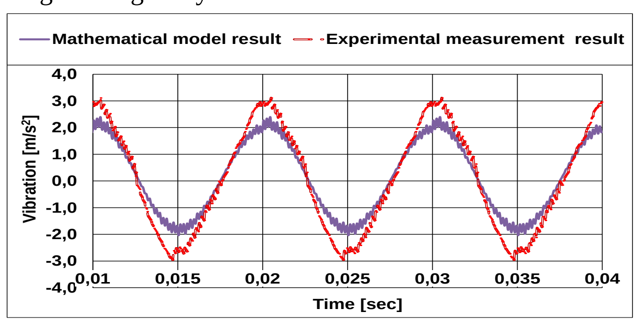

Figure 12. *Results of the vibration level between experimental measurement and the mathematical model in case the magnetic-leg and yoke have not been fixed*

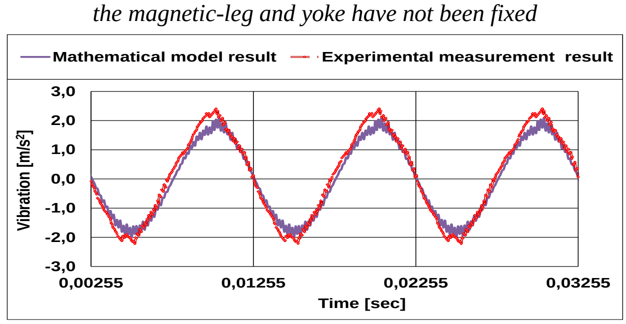

Figure 13. *Results of the vibration level between experimental measurement and mathematical model in case the magnetic-leg and yoke have been fixed.*

Figures 12 and 13 show us that the results of the vibration level via experimental measurement are higher than those of the vibration level via the mathematical model method. The main reason for the above deviation is that the experimental measurement method has to mention the vibration of the transformer coil as well.

Compared with the results of the mathematical model, the results of experimental measurements dropped down more than 6%. It is compatible with theoretical and experimental calculations.

Figure 14. *Results of the effective-vibration level in case the magneticleg and yoke have not been fixed.*

Figure 15. *Results of the effective-vibration level in case the magnetic-leg and yoke have been fixed.*

Figure 14 and 15 show the effective-vibration level in case the magnetic-leg and yoke have not been fixed as a_{kk} =1.7m/s^2, and the effective-vibration level in case the magnetic-leg and yoke have been fixed as a_{ck} =1,5m/s^2 as mean it's reduced 11,76%.

4. Audible noises in transformer

Based on [7], the noise level Nc(dB) shall been interdepended by the weight of transformer M(tons), the average-length of magnetic-core L(meters) and the magnetic induction B (Tesla). The noise of the transformer has been measured by [12] as follows:

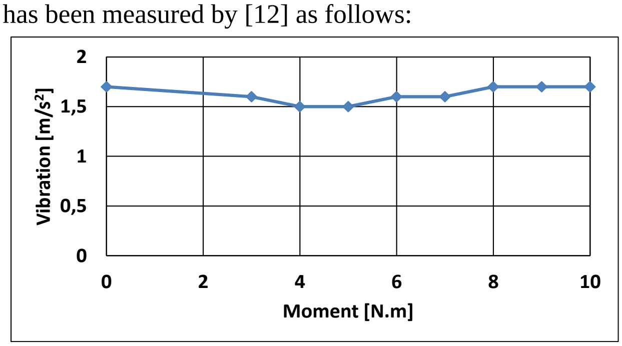

Figure 16. *The vibration level in case of using the wrench-force to tighten clampers (to keep the magnetic leg and yoke) with different torques*

From Figure 16, we can see that when using the wrench-force to tighten clampers (to keep the magneticleg and yoke of the transformer core), the min.value a=1.5m/s^2 corresponds to the tightening torque (4-5)N.m. If this tightening torque is converted into the tightening force, it is approximately 2600N. equal to the total force that has been calculated via the mathematical model.

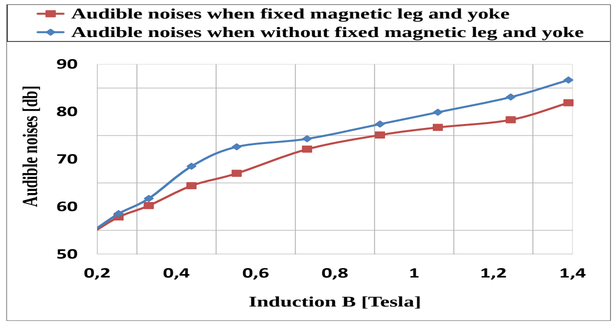

Figure17. *Noise levels before and after the magnetic-leg and yoke have been fixed tightly with tightening-torque (4-5) N.m*

Figure 17 shows that if the magnetic leg and yoke have been fixed tightly with the tightening torque (4-5) N.m, then the sound intensity is reduced by about 3,23 dB

5. Conclusions

In this engineering article, the authors have developed a new mathematical model. Through this mathematical model, they have examined the relationship between Mechanic and Magnetic which include the relevant elements such as deformation, displacement, vibration, magnetomechanic force.

The experimental results from the measurement of vibration and noise level with the clamping fixed magnetic-leg and yoke taken into account are of great importance. They help us determine the tension force to fix magnetic-leg and yoke of the transformer so that vibration level and noise level smallest. In this article so through experimental results and the results of the recently established mathematical model, we have noticed the tension force of clamping fixed magnetic-leg and yoke of the transformer equal with the total force of magnetostrictive force and magnetic force then the vibration – noise level shall be smallest.

Moreover, the frequency of power sources and the eigen frequency of transformers are also very important parameters that cause sound vibrations and noise in the steel core. This issue will be considered within the framework of further research papers.

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