Transmission of vibration of a power transformer from the internal structures to the tank

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ABSTRACT

Vibration-based transformer condition monitoring aims to identify the conditions of a transformer's internal structures, such as its windings and core, by measuring the vibration of the transformer tank. The correlation between the vibration signals from the internal structures and those from the transformer tank is dependent on the characteristics of the transmission path between them. Such vibration transmission is determined by direct mechanical coupling between the internal structures and the tank, and by indirect coupling through the fluid-structure interaction. This paper examines the vibration transmission characteristics based on experimental work on a 110kV power transformer. A series of dynamic and electrical tests were conducted on the power transformer with and without transformer cooling oil. Both internal and tank vibration were measured simultaneously. The effects of the transformer cooling oil on the vibration transmission are discussed. Finally, optimal locations on the tank for vibration measurement and monitoring of the transformer internal structures are presented.

1. INTRODUCTION

Power transformers are one of the most important components in the power industry. Failures in an operating power transformer may therefore cause huge economic loss, both directly and indirectly. Therefore, monitoring the performance of power transformers and preventing failures has practical significance. Vibration monitoring technique has been used for power transformers for a few decades. They measure the characteristic vibration of the transformer tank that transmits from the internal structures, such as windings and core, and use this to monitor their conditions and detect failures in the transformer's internal structures. A distinct merit of this vibration method is that it allows continuous non-invasive on-line monitoring and identification of transformer problems instantaneously.

As a new technique, most research work has so far concentrated on the vibration mechanisms of the transformer's internal structures, because they are the sources of tank vibration and most transformer failures also occur at these parts. However, only the tank vibration is available for practical condition monitoring purposes, which means that all the diagnosis of the internal structure must be based on vibrations measured on the tank. This requires a clear understanding about vibration transmission from the internal structure to the tank. This transmission is affected by mechanical coupling and fluid-structure interaction, which is quite complicated for theoretical modelling. Thus, more experimental works are required.

However, due to the limitations of economic cost and the experimental environment, most previous experiments on this vibration transmission issue were conducted on relatively small laboratory transformers (Pan, Wang and Jin, 2010).

This paper will report some experimental results from a three-phase 110kV power transformer. Vibrations on the transformer windings, core, and tank were measured simultaneously. The measurement was conducted for the tank with and without cooling oil, so that the effects of the oil on the vibration transmission could be examined. Furthermore, the transformer vibrations were excited by two kinds of forces in the experiment. One was a hammer impulse force, and the other was an electromagnetic force induced by a common 50Hz power support. The former impulse test can provide the structural vibration response of the transformer, and a preliminary vibration transmission function at all frequencies of interest. Meanwhile, the latter electrical test can give more practical results, which can be directly used for the development of the vibration-based condition monitoring method.

In the first part of this paper, vibration transmission of the dry transformer is discussed. Then, by comparing transformer vibration with and without cooling oil, the effects of the oil on vibration are demonstrated. The last part of this paper focuses on practical transformer vibration with cooling oil. The transmission loss and the coherence between the internal vibration and the tank vibration are the key focuses of this part, as the reliability of condition monitoring of the transformer's internal structure is dependent on the acceptable signal-to-noise ratio of the vibration signals measured on the tank and on a high coherence between the internal and tank vibrations.

2. THE TESTED TRANSFORMER

The tested transformer is a three-phase 110kV power transformer manufactured by JSHP Transformers (see Figure 1). During the experiment, the accessory structures, including the oil tank, oil pump, heating panels and regulating winding circuit, were removed considering the experimental environment. The winding and core vibration is the dominated componennt of transformer vibration.

The voltage ratio of the transformer is 110kV to 10.5kV. The current ratio is 262.4A to 1587.3A. The dimensions of the transformer are listed in Table 1.

Figure 1: The tested transformer before assembly*. (*All the tests were implemented after assembly.)

Table 1: Dimensions of the tested power transformer

Tank length	**Tank height**	**Tank width**	**Tank thickness**
4990mm	2880mm	1670mm	8mm
Core length	**Core height**	**Core diameter**	**Core window height**
3270mm	2730mm	620mm	1530mm
Primary winding diameter	**Primary winding height**	**Secondary winding diameter**	**Secondary winding height**
1119mm	1330mm	822mm	1340mm

3. VIBRATION TRANSMISSION THROUGH MECHANICAL JOINTS

There are two paths for a transformer's internal vibrations to transmit to the tank. One path is through the mechanical joints between the internal structures and the tank. The other is through fluid-structure interaction. In most power transformers, the windings and core are only joined with the tank at its bottom plate. This means that for plate in a dry transformer without oil, internal vibrations can only transmit to the tank through the bottom. Therefore, to study the vibration transmission through the mechanical joints, the dry transformer is tested first.

A transmission function is used here to describe the vibration transmission. For example, when vibration V_A at point A of the internal structure and vibration V_B at point B of the tank are both recorded, their ratio V_B / V_A is defined as the vibration transmission function on the path A to B, which describes the vibration transmission loss from A to B.

To excite the internal vibration, an impact hammer was first applied to the transformer to generate an impulse force, and then a common 50Hz electrical current was applied to the transformer winding to generate an electromagnetic vibration. Hammer induces free vibration, so it is able to indicate the frequency response of the transformer, whereas the electrical excitation is forced vibration response at certain frequencies.

Figure 2 shows the impact hammer test experiment. The impact location is on the top of the centre limb of the transformer core, and perpendicular to the plane of the core. The internal vibration used here was measured at the middle part of winding B. The tank vibrations were measured at 15 points on the tank wall as shown in Figure 3. Location T1 on the tank corresponds to the top of the Phase C winding, and T5 is near the bottom. The distance from T1 to the top edge of the tank is 905mm, and from T5 to the bottom edge of the tank is 975mm. Likewise, T6 to T10 and T11 to T15 are similarly located on Phase B and Phase A windings, respectively. The hammer force was also recorded for calculating the vibration response of the transformer structure. The ratio of the vibrations of the winding and the tank yields the vibration transmission function.

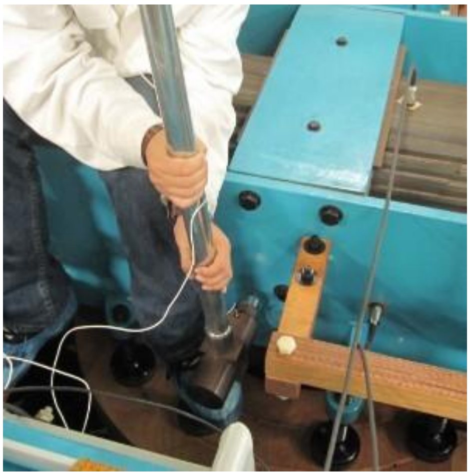

Figure 2: Impulse hammer test

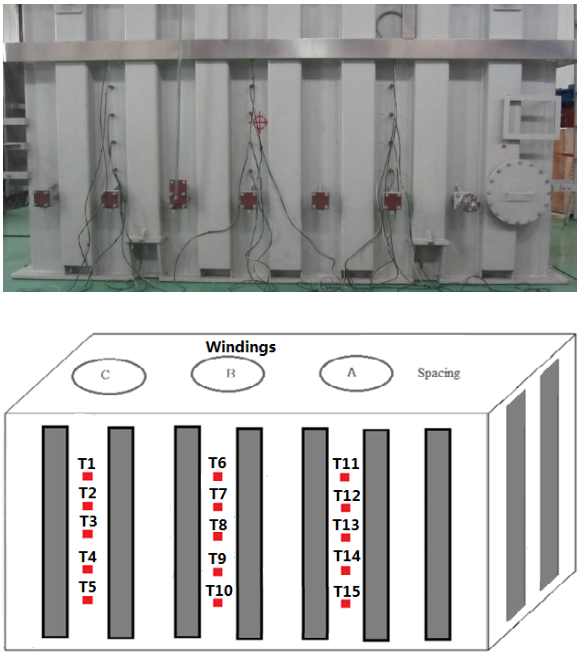

Figure 3: Accelerometer locations on the tank

The top and middle graphs in Figure 4 are the vibration responses of the winding and that at location T6 of the tank, respectively. Obviously, the vibration response on the tank is much smaller than that on the winding due to transmission loss between the winding and the tank. The bottom diagram is the vibration transmission function from the winding to the tank at point T6. It is clear that the transmission loss at different frequencies shows different values. For example, the loss at around 100Hz is about -40dB, which means that the tank vibration at 100Hz is 100 times less than the internal core vibration. However, the loss at 300Hz is only -7dB, so that about 55% of the internal vibration can transfer to the tank at 300Hz. The uneven loss distribution is mainly affected by the resonance response and mode shapes of the transformer tank.

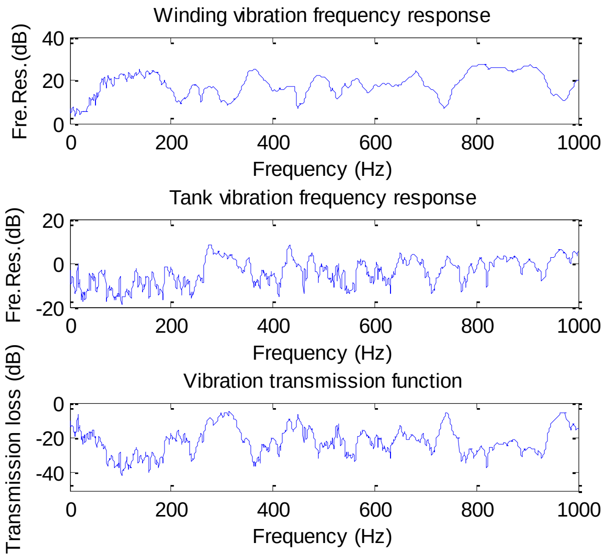

Figure 4: The vibration response of the core (top) and tank at point T6 (middle), and the vibration transmission function from the winding to the tank point at T6 (bottom).

Figure 5 compares the vibration transmission function at points T6 and T10 of the tank. The peak frequencies at these two locations are almost the same, but the average loss at the tank bottom (T10) is less than at the tank top (T6). The average loss at T6 within 1000Hz is 87.8%, but the average loss at T10 is 83.4%. In fact, at the peak frequencies, such as 300Hz and 750Hz, the vibration at the tank bottom could be several times larger then that at the top. As mentioned before, the reason for this is that most of the internal vibration can only transmit to the tank from the bottom plate when no oil is in the tank.

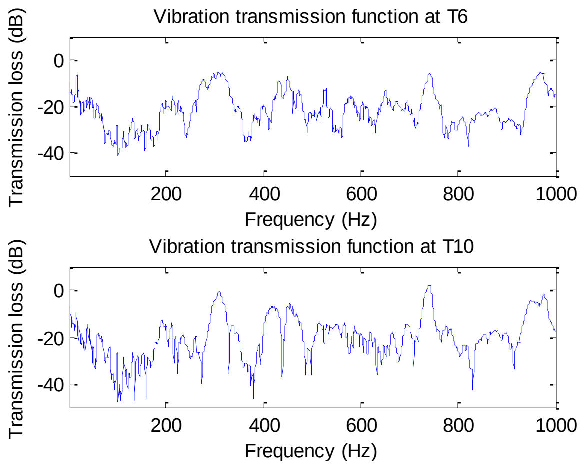

Figure 5: Comparison of the vibration transmission function at the top of the tank (T6) and at the bottom of the tank (T10).

The transformer vibration was also generated electrically. In contrast to the impulse force excitation at the top of the centre limb, the electrical excitation is applied to the entire phase B winding. The transformer was working at the rated current without cooling oil. Because the transformer vibration was inducted by the electromagnetic force, the 50Hz power supply gave rise to transformer vibration at a 100Hz fundamental frequency and its harmonics (Garcia and Burgos, 2006). Figure 6 shows the transformer vibrations on the winding and the tank. The tank vibrations are much smaller than those of the winding. The vibration at the tank bottom is also larger than that at the tank top. This observation agrees with the impulse test quite well. Another interesting observation is that the winding vibration at the 200Hz harmonic is only 1/20th of the 100Hz fundamental vibration, but this trend is reversed for the vibration on the tank. This can be explained by Figure 4, where the transmission loss at 100Hz is much greater than at 200Hz. Table 2 compares the transmission losses measured by the impulse test and by the electrical test at 100Hz and 200Hz. The two tests give almost consistent results, especially at 100Hz. The small differences are mainly caused by the different exciting forces in these two tests. The hammer impulse force is a single-point force, but the electromagnetic force is a distributed force.

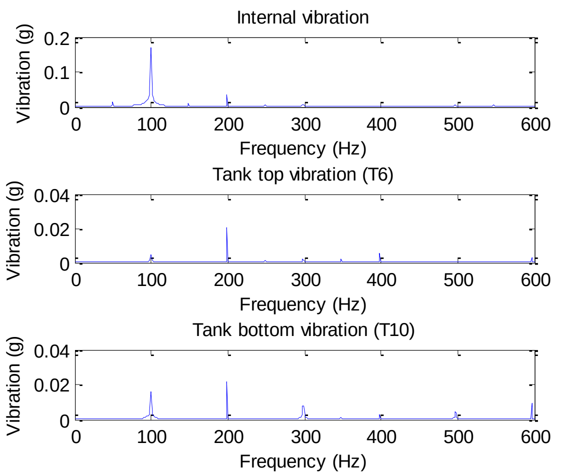

Figure 6: Electrically excited vibration of the dry transformer

Table 2: Comparison of the vibration transmission losses between the impulse test and the electrical test on the dry transformer.

Vibration transmission loss		Impulse test*	Electrical test
Tank top (T6)	100Hz	97.8%	97.3%
	200Hz	50.1%	44.0%
Tank bottom (T10)	100Hz	92.9%	90.8%
	200Hz	20.6%	38.4%

* Because the transmission function measured by the impact hammer test has some fluctuations with frequency, the transmission loss of the impulse test in the table is an average loss over a 10Hz frequency band. For example, the loss at 100Hz is the average loss in the frequency range from 95Hz to 105Hz.

4. EFFECTS OF TRANSFORMER OIL

Transformer cooling oil in a tank introduces another vibration transmssion path. The effects of the oil on the transformer vibration transmission are mainly shown in two aspects. On one hand, the coupling between the oil and the windings and core provides a vibration transmission path to the tank. On the other hand, the oil also provides damping and mass loading to the vibration in the tank. These two effects work on the vibration transmission in two opposing ways. As a result, the overall effect of the oil on the tank vibration is quite complicated. Nevertheless, the experimental results may shed some light on this effect.

With the transformer tank filled with cooling oil, the same impact hammer and electrical tests were conducted. Figure 7 shows the results of the impact hammer test. The top diagram is the vibration response of the winding. By comparing it with the top diagram of Figure 4, significant differences are observed in the frequency responses and transmission functions for the transformer with and without the cooling oil. Due to the fluid loading, the winding vibration response becomes much smoother. A reduced number of peaks and an increased frequency bandwidth of the resonant peaks can also be observed. However, the overall vibration level does not have obvious changes. The middle and bottom plots of Figure 7 are the vibration transmission functions at the top and bottom of the tank, respectively. Compared with the transmission functions without oil (Figure 5), the transmission loss increases with the frequency due to the damping and mass loading effects of the oil. In other words, the cooling oil works like a low-pass filter that attenuates the high frequency vibration transmission. Meanwhile, the average transmission loss in the low frequency range (<380Hz) at the top of the tank is 77%, which is smaller than the value at the bottom of the tank, 86.2%. It is also significantly lower than that without the oil, 87.8%. This means that more internal vibration, especially at the lower frequencies, is transmitted to the tank walls through the oil by the fluid-structure interaction.

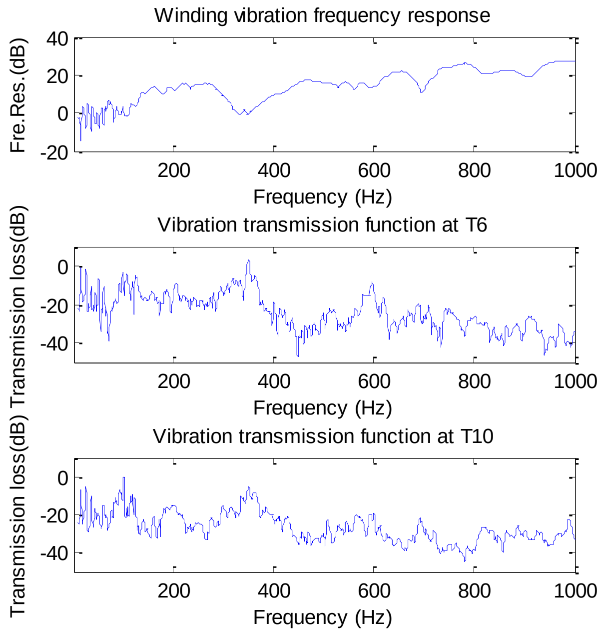

Figure 7: Transformer internal vibration response and transmission functions on the tank when the tank is filled with oil.

Figure 8 shows the electrical vibrations of the transformer with oil, and Table 3 gives the corresponding vibration transmission losses at 100Hz and 200Hz when only Phase B is excited. Comparing these with the results of the dry transformer (Figure 6 and Table 2), the vibration transmission loss at the fundamental frequency of 100Hz shows a significant reduction. Considering the higher frequency vibration at 200Hz, the transmission loss is larger than that from the dry transformer. This result agrees with that from the impact hammer test.

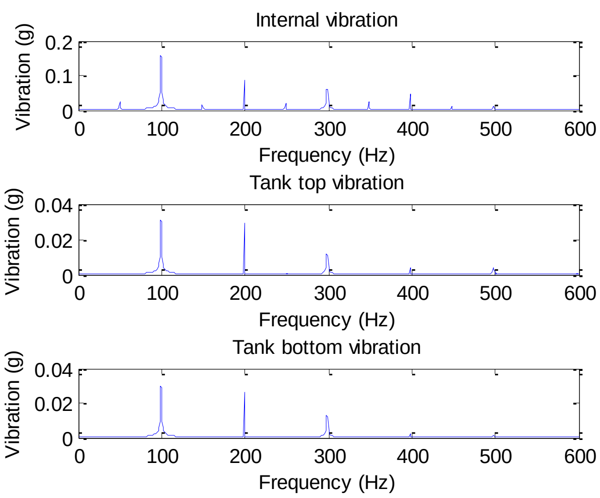

Figure 8: Transformer online vibration with oil.

Table 3: Comparison of the vibration transmission losses between the impulse test and the electrical test on the transformer with oil.

Vibration transmission loss		Impulse test	Electrical test
Tank top (T6)	100Hz	82.2%	80.3%
	200Hz	74.9%	67.0%
Tank bottom (T10)	100Hz	84.2%	81.8%
	200Hz	80.1%	70.4%

According to these experimental results, the effects of the transformer cooling oil can be summarised as follows:

1. The vibration frequency response of the transformer winding becomes smoother and with fewer and broader peaks due to oil loading.
2. The vibration transmission to the top of the tank walls in the low frequency range is enhanced due to increase vibration transmission paths through the oil.
3. The vibration transmission to the tank in the frequency range is attenuated due to the oil's mass loading effect.

5. OPTIMAL TANK LOCATIONS FOR VIBRATION MONITORING

The purpose of the vibration monitoring method is to use transformer tank vibrations to detect and predict the health conditions of the transformer's internal structures. In practice, it is only possible to use a small number of accelerometers to measurs the transformer tank's vibration. Therefore, in order to accurately predict the internal conditions while using only a limited number of accelerometers, the measurement locations on the tank should be chosen carefully.

Once the mechanisms for transformer vibration and vibration transmission paths are identified, the optimal locations on the transformer tank for vibration measurement can be determined. The tank vibration measurements must meet two important requirements. Firstly, the signal-to-noise ratio of this measured tank vibration should be as high as possible, which means the measurement location on the tank must have a low vibration transmission loss. Secondly, the measured tank vibration must closely correlate to the internal vibration so that it can represent the conditions of the internal structure appropriately. This requires a high coherence between the tank vibration and the vibration of the internal structures.

During the experiment, both the internal vibrations and the tank vibrations were recorded simultaneously, so that the results could indicate the optimal locations on the tank for the vibration measurements.

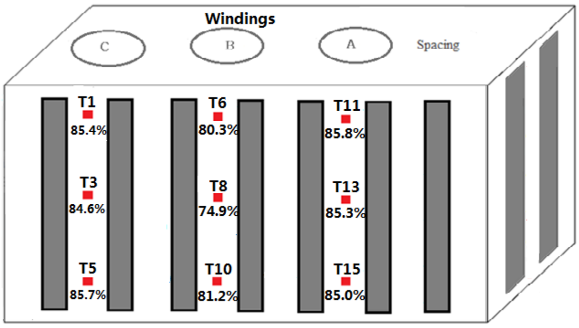

Figure 9: Distribution of vibration transmission losses on the tank at 100Hz when only Phase B is excited electrically.

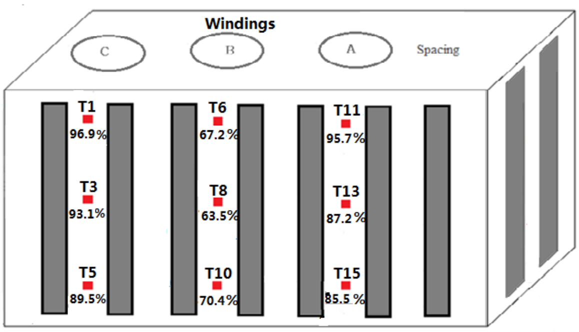

Figure 10: Distribution of vibration transmission losses on the tank at 200Hz when only Phase B is excited electrically.

It is well known that transformer vibration due to electrical excitation is dominated by components at 100Hz and its harmonics (Toshikazu, et al, 2002). Figures 9 and 10 show the distribution of vibration transmission losses on the front surface of the tank at 100Hz and 200Hz, respectively, when only Phase B is excited. They demonstrate similar trends where: (1) the transmission loss at the centre of the surface is the lowest; (2) the higher losses are found near the corners of the surface. According to this observation, as a low transmission loss means a high vibration-to-noise ratio, it appears that the best measurement locations are at the centres of the tank surfaces. However this vibration distribution is dominated by the vibration of the Phase B winding. Therefore, it is necessary to verify the distribution when all three phases are excited.

Figures 11 and 12 give the distributions of vibration on the tank surface when all three phases are excited. The same trend as in the single phase test can be observed. The closer to the centre of the tank wall, the lower the transmission loss is.

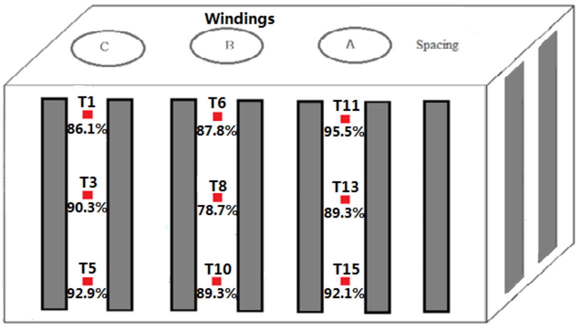

Figure 11: Distribution of vibration transmission losses on the tank at 100Hz when three phases are excited electrically.

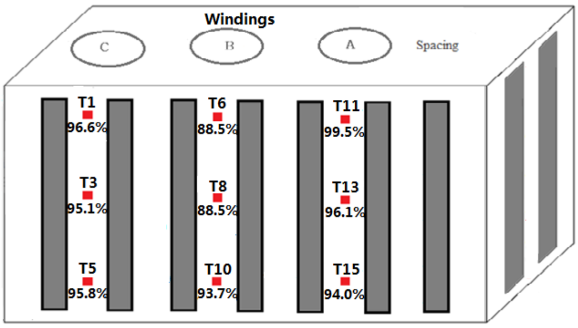

Figure 12: Distribution of vibration transmission losses on the tank at 200Hz when three phases are excited electrically.

The above results indicate that the vibration at the centre of the tank wall has the highest signal-to-noise ratio. The other important aspect is the coherence between the internal and tank vibration signals. Figure 13 shows the coherence functions at tank points T8, T3 and T1. Theoretically, for a transformer driven by a 50Hz power support, its vibration should be located at 100Hz and its harmonics. However, due to some nonlinear effects of the transformer, such as magnetic hysteresis and external disturbance, 50Hz vibrations and its harmonics also exist (as seen in the top diagram of Figure 8). Therefore, for clarity, Figure 13 also shows the coherence around 50Hz and its harmonics. It is obvious that in the low frequency range, the coherence at all the measurement locations is almost equal to 1. However, in the high frequency range, the vibration measured at the centre of the tank gives the best coherence. Because the main vibration components are concentrated at low frequencies, such as 100Hz and 200Hz, all of the signals meet the basic requirements regarding the coherence issue. However, although the high frequency transformer vibration is small, it still carries some useful signatures of the internal structural vibration (especially for those related to the core's health conditions). As a result, the centre of the tank wall is still the best location for vibration measurement.

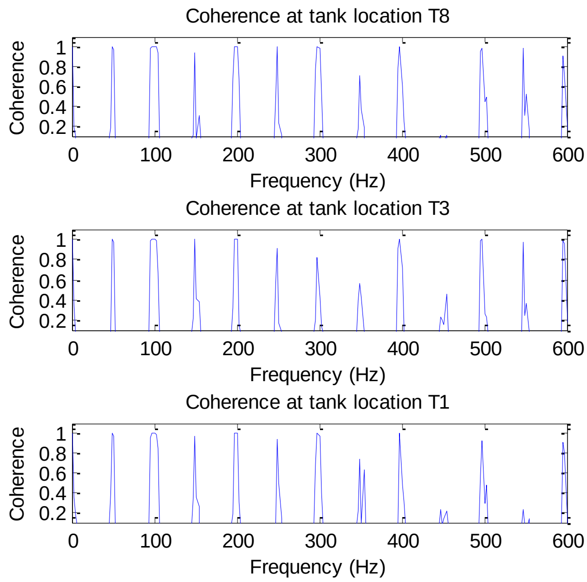

Figure 13: Vibration coherence functions between the tank and internal structures at different tank locations.

6. CONCLUSIONS

This paper reported an experimental study on the vibration of a 110kV power transformer. A unique feature of this experiment was that it produced simultaneous measurements of the tank vibration and the vibrations of the internal windings and the core. No similar work on such a high voltage power transformer has been reported before, especially in the case of electrically excited vibrations.

When the transformer tank is not filled with cooling oil, most of the internal vibration transmits into the tank through its bottom plate. However, when the transformer is filled with cooling oil, the oil provides not only a fluid loading to the tank wall, but also a new path for vibration transmission. As a result, the low frequency vibration on the upper part of the tank increases. However, due to the damping and mass loading effects of the oil, the high frequency vibration on the tank reduces. This finding is helpful in linking the windings and core vibrations to the tank vibration, and in providing useful information for existing transformer vibration monitoring method. It was also found that the optimal tank location on the tank for vibration monitoring may be at the centre of each tank wall.

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REFERENCES

Toshikazu, N 2002, '*Estimation on on-load vibration of transformer windings'*, IEEE, 2002, pp. 1378-1382.

Jin, M & Pan, J 2011, '*Effect of insulation paper ageing on the vibration characteristics of a winding disc'*, Proceedings of ACOUSTICS 2011, 2-4 November, Gold Coast, Australia.

Uchiyama, N, et al 2000, '*Axial Vibration Analysis of Transformer Windings with Hysteresis of Stress-and-Strain Characteristic of Insulating Materials'*, IEEE, 2000.

Jin, M & Pan, J 2010, '*A study of vibration properties of parallel beams coupled by insulation elements'*, Proceedings of 6th Austalian Congress on Applied Mechanics, December.

Pan, J, Jin, M & Wang YX 2011, *'Vibration of Power Transformers and its Application for Condition Monitoring'*, 14th Asia Pacific Vibration Conference 5-8 December, The Hong Kong Polytechnic University.

Pan, J, Wang, J & Jin, M 2010, *'Structural vibration of a transformer'*, Proceeding of the 17th International Congress of Sound and Vibration, Cario.

Garcia, B & Burgos, JC 2006, '*Transformer tank vibration modeling as a method of detecting winding deformations-part I: Theoretical foundation'*, IEEE Transactions on Power Delivery, 2006, Vol. 21, No. 1, pp. 157-163.