Modelling of Piezoelectric Sensor with Different Materials Approach for Partial Discharge Detection on Power Transformer: PZT-5H, ZnO and A/N

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Abstract. The acoustic emission (AE) technique is one of the unconventional methods of partial discharges (PDs) detection. It plays a most important role in oil-filled power transformers diagnostics because it enables the detection and online monitoring of PDs as well compared to the conventional method for PDs detection which are not suitable for on-site measurement due to electrical disturbance. In this paper, the acoustic based on piezoelectric sensor by different material is modelled in order to be able to obtain PDs signal occurred in power transformers. Modelling of a piezoelectric sensor with different material which is PZT-5H, ZnO, and A/N is approached in order to investigate the performance of resonant frequency, electric potential, and the performance in processing in order to match the range of AE detection. Piezoelectric materials have become very useful in processing devices because of their electrical-mechanical mutuality. Study was performed on frequency target of PDs should be higher and in the range of 10 kHz - 300 kHz in order to prevent the power transformer from failure or breakdown and it has been found out by proven from analytical and simulation result by using the Finite Element Method (FEM). Based on this information, acoustic sensor is analyses with different types of cantilever beam and piezoelectric material and different length dimension of the beam in order to analyses the performance between them. Based on the result, the piezoelectric material that be chosen in this project is ZnO due to its high piezoelectric coupling and environmental friendly is used in order to support green technology compared to others material discussed which is harmful even though produced high performance. This detection method gave some improvement in monitoring system PD activities in the transformer’s tank.

1. Introduction
Power transformers are a strategic component of the electric power system. It is normally believed that the oil–paper insulation system is designed in order to work reliably for 30–40 year [1-3]. However, there are many power transformers installed all around the world, which operate without failure above this age. Piezoelectric layer is very important in fabricating the sensor. The thin film is one of the important factors that improve the performance of the device in term of sensitivity and accuracy in
Piezoelectricity is an electrical charge, which produces when certain material experience mechanical stress [5-6].

PDs at the power transformer occurs because of unscheduled maintenance, aging of equipment, breakdown of insulation, gas bubbles in insulation liquid and manufacturing error [7-8]. In order to maintain constant and high as possible transformer performance it is essential to control, detect and measure PD phenomena. There is most common methods used such as chemical, electrical or optical detection, however, there have limitation to apply this method as it is impossible to obtain the location information using their technique. For example, chemical detection of PD signal is by detecting the changes on chemical composition of the insulating materials in the transformer [9-10]. The sample of oil from the tank need to be taken out and analysed to spot the different level of gases. The test is shown in [10-12], called as dissolved gas analysis (DGA) and it required time consumption to analyse the result. The method also unable to point out the PDs signal source and it cannot be used in real time and online condition monitoring purposes. A large portion of HV transformer failures is caused by faults of oil-paper insulation, which often start with the PDs. The PDs signal generated an electromagnetic emission which is can be detected by a piezoelectric sensor in the frequency band started from 10 kHz to 300 kHz and the tendency to stay in range 100 -150 kHz [5-13]. Currently piezoelectric sensor is widely used and known as a popular technique for AE detection that proposed for small size and low frequency detection [14].

Alternately, the mechanical force will be created when electricity applied on the same material. The most commonly used piezo-materials in AE devices are lead zirconate titanate (PZT), zinc oxide (ZnO), and aluminum nitride (A/AlN) [14-15]. The material performance that widely used in an industry nowadays is likes PZT-5H due to the high coupling factor which is the main reason why PZT-5H is preferred over other piezoelectric materials [15]. However, PZT-5H contained lead (PbO) up to 60% of weight, which is not suitable for everyday application. The presence of PZT-5H has become a major concern for environmental issues where PbO can released to the atmosphere during production of PZT-5H [5,16].

Each of them has different properties such as cost, piezoelectric coupling coefficients, attenuation, temperature sensitivities and propagation velocity. For example, A/AlN has attracted considerable attention in recent years owing to its unique properties [18]. Specifically, its high thermal conductivity, moderate piezoelectricity, low dielectric and acoustic losses and high acoustic wave velocity. However, in this study, ZnO has been chosen as it is a material with great advantages for a piezoelectric substrate [17,18]. ZnO is a n-type semiconductor material and used for several sensor devices considered its sensitivity and easy doping method to improve sensing performance [19].

In this research, the performance of different types of cantilever beam by FEM are presented. Two types of the cantilever beam profile are designed to investigate the performance of mechanical to electrical which are fixed free end (FFE) and fixed both ends (FBE). ZnO material is proposed in this research due to its high piezoelectric coupling and environmental friendly in processing compared to the others material which is from time to time is not suitable for everyday application and silicon (Si) material is selected to use as the supporting beam. A comparison between various piezoelectric materials is summarized in Table 1.

The comparison between piezoelectric materials have been discussed and can be concluded that among the three materials, A/AlN has emerged as the most suitable and reliable one for use in harsh environments such as high temperature and humidity environment since it remains chemically stable [1]. However, its piezoelectric response is much lower compared to PZT-5H [15]. On the other hand, PZT-5H is not environmentally friendly to the industries even though it have an effective way to increase its piezoelectric response [20]. Nevertheless, a lot of work needs to be done to further improve its piezoelectric output by exploring new doping materials so as to make it comparable to PZT-5H based devices. The ZnO material is more suitable and have an advantages which are environmentally friendly and not harm even though it is tough in processing the process [15,21].
Table 1. Comparison between piezoelectric materials [19].

| Property                  | PZT-5H | ZnO  | A/N |
|---------------------------|--------|------|-----|
| D33                       | High   | Moderate | Low |
| D31                       | High   | Moderate | Low |
| Electrical resistance     | High   | High   | High |
| Dielectric constant       | High   | High   | Low |
| Sound velocity            | High   | Moderate | Low |
| Acoustic losses           | High   | Moderate | Low |
| GHz capability            | Poor   | Poor   | Good |
| Ferroelectricity          | Yes    | Yes    | No  |
| Environment               | Unfriendly | Friendly | Friendly |
| Density                   | Heavy  | Light  | Light |
| Processing                | Easy   | Moderate | Difficult |

2. Piezoelectric Fundamental Study

2.1. Piezoelectric Parameter

The direct and indirect piezoelectric effect is often represented by a pair of linear constitutive equations as follows, where $S$ is strain i.e. relative deformation, $s^E$ is compliance, inverse of elasticity, under constant electric field, $T$ is applied stress, $d$ is dielectric displacement, and $\varepsilon^T$ is dielectric constant under constant stress [5-22].

$$S = s^E \cdot T + d \cdot E \quad (1)$$

$$D = d \cdot T + \varepsilon^T \cdot E \quad (2)$$

In order to determine the resonant frequency of the cantilever beam, the Stoney’s equation which relates cantilever end deflection $d$ to applied force, $d$ is referred:

$$d = \frac{3d(1 - v)}{E \left( \frac{L}{R} \right)^2} \quad (3)$$

Where $v$ is the Poisson’s ratio, $E$ is young modulus, $l$ is the cantilever length and $h$ is the cantilever height. The cantilever’s spring constant, $k$ can be expressed as follows which is for FFE and FBE respectively:

$$k = \frac{3EI}{l^3} \quad \text{and} \quad k = \frac{192EI}{l^3} \quad (4)$$

since $I$ is known as moment of inertia for cantilever beam and the equation for the moment of inertia is as follows:

$$I = \frac{bh^3}{12} \quad (5)$$
where \( b \) is formed to be the width of the cantilever and \( h \) is known as thickness. The resonant frequency can therefore be increased due to the thickness or the length of the cantilever beam. The following equation is used to identify the resonant frequency:

\[
f_{(res)} = \frac{1}{\pi} \sqrt{\frac{k}{m}}
\]

(6)

when mass, \( m = \rho \cdot h \cdot l \cdot w \). In this situation, \( \rho \) is the resistivity, \( h \) is known as the height of the cantilever, \( l \) is known as cantilever length and \( w \) is the width of the cantilever. The resonance frequency is presented to be a purpose of the spring constant and mass of the cantilever.

2.2. Type of Beam Based on Support

A beam is a long, slender member, a 2d element in a structure having relatively longer span than the depth. The beam is designed to carry the bending moment and the shear forces if any. Based on the supports of the beam, Figure 1 shows some of the classifications of the beam [17,18]. The following are the 6 different types of beams based on end supports or restraints. By the all of the explanations in Table 2 decide that the cantilever and fixed ended beam is most suitable for this research.

![Figure 1. Type of Cantilever Beams [20].](image)

| Type of beam          | Explanation                                                                 |
|-----------------------|-----------------------------------------------------------------------------|
| Cantilever            | A beam which is fixed at one end and free at the other end is known as cantilever beam, or from the statics point of view a beam with fixed support at one end resisting all the vertical, horizontal and bending moment produced as a result of loading of the beam and is free at the other end is a cantilever beam. |
| Simply supported      | As the name suggests a beam which is supported or resting freely on supports at its both ends is known as simply supported beam or from a mechanics point of view, a beam with both hinge support resisting horizontal and vertical forces and roller support fixing only one vertical force. If the end portion of the beam is extended beyond the support such a beam is known as overhanging beam. Mostly in overhanging beam one support is hinge support while other is roller support having one end as free like a cantilever. |
| Overhanging           | A beam which is provided more than two supports or is continuous over more than two supports is known as continuous beam. Usually in frame structure a continuous beam is used which have both positive and negative moments you will be able to calculate later on. |
| Continuous            | A beam which is fixed at one end and free at the other end is known as cantilever beam, or from the statics point of view a beam with fixed support at one end resisting all the vertical, horizontal and bending moment produced as a result of loading of the beam and is free at the other end is a cantilever beam. |
| Fixed ended           | As the name suggests a beam which is supported or resting freely on supports at its both ends is known as simply supported beam or from a mechanics point of view, a beam with both hinge support resisting horizontal and vertical forces and roller support fixing only one vertical force. If the end portion of the beam is extended beyond the support such a beam is known as overhanging beam. Mostly in overhanging beam one support is hinge support while other is roller support having one end as free like a cantilever. |
| (f) Cantilever, simply supported | A beam which is provided more than two supports or is continuous over more than two supports is known as continuous beam. Usually in frame structure a continuous beam is used which have both positive and negative moments you will be able to calculate later on. |
Table 2. Explanation for the function [20] (Continued…).

| Type of beam          | Explanation                                                                                                                                 |
|-----------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| Fixed ended           | A beam whose both ends are fixed or built-in walls, are known as fixed beam. A fixed beam is also known as built-in or encased beam. A fixed beam usually have reinforcement that is going through the beam into the column. |
| Cantilever, simply supported | A cantilever with simply supported is a little modification of the cantilever beam, if the free end of the cantilever beam is placed on a roller support than the resultant beam will be propped cantilever beam. |

3. Piezoelectric Sensor Modelling using FEM

3.1. Simulation Setting

FEM software presents a platform for solving and modelling issues related to science and engineering. Interactive desktop window with model builder window gives access to all functions. There are traditional types of analysis currently: 2D modelling and 3D modelling [21,22]. In terms of accuracy, 2D modelling yields less accurate results while 3D modelling allows relatively better accurate results. In these simulations, contains two primary analyses which are solid mechanic analysis and eigen frequency analysis to analyse the concept of theoretical approach, cantilever beam sensor modelling on the piezoelectric layer and supporting beam, and piezoelectric configuration materials.

3.2. AE Sensor Cantilever Beam Model Approach

There are twelve different models size named as summarized in Table 3. The design is simulated in order to analyze the comparison result between all the piezoelectric materials which is PZT-5H, ZnO, and AlN and size of the beam to identify the high frequency detector sensor in order to detect PDs signal.

Table 3. Summarization of the beam dimension.

| Type of sensor | Beam Size | Thickness | Si Thickness |
|----------------|-----------|-----------|--------------|
|                | Length (mm) | Width (mm) | Piezo-material (mm) | Thickness (mm) |
| AE 1           | 4         | 4         | 0.001        | 0.45          |
| AE 2           | 5         | 4         | 0.001        | 0.45          |
| AE 3           | 6         | 4         | 0.001        | 0.45          |
| AE 4           | 7         | 4         | 0.001        | 0.45          |
| AE 5           | 8         | 4         | 0.001        | 0.45          |
| AE 6           | 9         | 4         | 0.001        | 0.45          |
| AE 7           | 10        | 4         | 0.001        | 0.45          |
| AE 8           | 11        | 4         | 0.001        | 0.45          |
| AE 9           | 12        | 4         | 0.001        | 0.45          |
| AE 10          | 13        | 4         | 0.001        | 0.45          |
| AE 11          | 14        | 4         | 0.001        | 0.45          |
| AE 12          | 15        | 4         | 0.001        | 0.45          |

Figure 2 shows the model of the cantilever beam structure which is made up of Si as the supporting beam with a thin layer of piezoelectric material been deposited on top of the Si beam. The thickness of the piezoelectric layer is 0.001 mm and the Si based layer is fixed 0.45 mm respectively. There are several materials that have been tested for supporting beam for example nickel, silica glass and tungsten [17,24]. However, Si is popular around researchers [15,17,24] and approved that Si material is better than others.
material due to its mechanically strong and elastic material which is contributing to reliable device [17, 18]. The Si layer also functions as a mass-spring system and Si is stable up to high temperature and has a high electrical conductivity [23].

The selection of the size of supporting beam was analyzed by testing the size approached for these analyses which is starting from 2 mm x 2 mm, 4 mm x 4 mm to 10 mm x 10 mm in order to obtain the highest frequency that can support the piezoelectric material to detect the PDs signal. In purpose of testing the materials and the sizes of a cantilever beam, the frequency target for this sensor should be higher and in the range of 10 kHz – 300 kHz so that the signal of PDs on power transformer can be detected. The cantilever beam is modelled from two blocks which are the upper layer is the piezoelectric material (blue) and the lower layer is supported beam (gray), which together build to analyze the performance on getting the suitable size.

3.3. Cantilever Beam Structure
There are two structural designs which are commonly used by researchers as the substructure to support the piezoelectric thin film and promote high stress to be transduced into electrical signal, these being the diaphragm and cantilever. For each sensor, the result is obtained 2 times, once at 1 fixed constraint named as fixed free end (FFE), and second time at 2 fixed constraints named as fixed both ends (FBE). The constraint was applied to the fixed support of the cantilever in order to avoid translation and rotations [19] of the beam due to its capability to scavenge power from low-level ambient vibrations and high-level respectively as shown in Figure 3 which obtain from the simulation parts. Table 4 illustrates the materials testing properties, which are PZT-5H, ZnO, AlN, and Si materials used in these piezoelectric sensor model analyses.

![Cantilever beam structure](image1)

**Figure 2.** Cantilever beam structure

![Simulated module](image2)

**Figure 3.** Simulated module at: (a) One fixed constraint (b) Two fixed constraints.
Table 4. Material properties [5,21].

| Material Properties | PZT-5H  | ZnO     | A/N     | Si      |
|---------------------|---------|---------|---------|---------|
| Young modulus, E (Pa) | 56 x 10^9 | 6.83 x 10^9 | 300 x 10^9 | 170 x 10^9 |
| Density, p (kg/m^3)  | 7500    | 5680    | 3300    | 2329    |
| Poisson’s Ratio      | 0.36    | 0.20    | 0.22    | 0.28    |

4. Result and Discussion

4.1 Introduction
This section dedicated to discuss the results of simulation and modelling of piezoelectric with an AE sensor based on the different materials approach. This section is divided into two parts which are evaluated on analysis result on size of Si as supporting beam and analysis result of different materials as piezoelectric layer.

4.1.1. Analysis Result on Size of Silicon as Supporting Beam
Each design for all of the plate’s dimensions has been simulated 2 times, first time with 1 constraint and the second time is 2 constraints along length of model dimensions. The dimensions of the model are being fixed except the dimensions of length. The higher the length dimension, the lower the resonant frequency will appear [14]. The fixed value 4 mm for width dimension is selected in this research due to insignificant effect on frequency resonant output as presented in [14,22].

Figures 4 and 5 are illustrated the results of resonant frequency at different dimensions of Si at different size of width and length. It is noticeable that Si with dimension 2 x 2 mm produces a higher resonant frequency, even though this dimension is too small and more suitable for MEMs technique. Next, for dimension 4 x 4 mm produces the second highest frequency compare to 6 x 6 mm, 8 x 8 mm and 10 x 10 mm which has shown the lower results. As well, it can be seen that plate where depth is smaller than width gives higher frequency. In addition models with 2 fixed constraints gave bigger frequency compared to 1 fixed constraint. These results indicate that for the sensor as supporting beam that will be used is Si, and the technique will be used is by clamped the beam using method FBE for generating higher frequency.

![Figure 4. Result of simulation on selecting the size of Si on FFE.](image-url)
4.2. Analysis Result on Different Materials as Piezoelectric Layer

Tables 5 - 8 and Figures 6 - 9 proves the results of comparison between performance of all selected materials proposed in this research analyses on frequency resonant and electric potential which is for type of FFE and FBE and have been seen that the A/N is produced highest resonant frequency followed to ZnO and PZT-5H. Other than that, among FFE and FBE, seem that the result for FBE was generated resonant frequency higher than FFE.

Moreover, for electric potential results shown that the PZT-5H generated highest result and proved that it is superior piezoelectricity followed to A/N and ZnO which generated lower electric potential. However, poor stability and loss of polarization with continuous usage are the major issues for PZT-5H. Their piezoelectric properties are also strongly affected by operating temperatures and due to brittleness they cannot be deformed mechanically for long duration [15,24]. Though, in this research was chosen for ZnO as piezoelectric layer as the characteristic is suitable enough for AE technique, which is pollution-free piezoelectric material and is free from limitations found with PZT [25] where might generate high frequency for the sensor to detect PD signals even though ZnO is smaller than PZT-5H and A/N. Based on this result, A/N is not chosen due to its processing of A/N is more challenging compared to PZT-5H and ZnO [5].

| Type of Sensor | PZT-5H | ZnO  | A/N  |
|---------------|--------|------|------|
| AE1           | 39.51  | 39.61| 39.81|
| AE2           | 25.51  | 25.38| 25.51|
| AE3           | 17.59  | 17.64| 17.73|
| AE4           | 12.92  | 12.95| 13.02|
| AE5           | 9.88   | 9.91 | 9.96 |
| AE6           | 7.81   | 7.82 | 7.86 |
| AE7           | 6.31   | 6.32 | 6.36 |
| AE8           | 5.21   | 5.22 | 5.25 |
| AE9           | 4.37   | 4.39 | 4.41 |
| AE10          | 3.73   | 3.74 | 3.76 |
| AE11          | 3.21   | 3.22 | 3.24 |
| AE12          | 2.79   | 2.81 | 2.82 |
Table 6. Types of Different Materials and Results of Resonant Frequency for FBE.

| Type of Sensor | PZT-5H | ZnO    | A/N    |
|----------------|--------|--------|--------|
| AE1            | 235.87 | 236.00 | 237.54 |
| AE2            | 154.95 | 155.30 | 156.07 |
| AE3            | 109.67 | 109.93 | 110.47 |
| AE4            | 81.19  | 81.38  | 81.79  |
| AE5            | 62.46  | 62.61  | 62.93  |
| AE6            | 49.52  | 49.63  | 49.88  |
| AE7            | 40.19  | 40.29  | 40.50  |
| AE8            | 33.27  | 33.35  | 33.52  |
| AE9            | 27.98  | 28.05  | 28.20  |
| AE10           | 23.87  | 23.93  | 24.05  |
| AE11           | 20.59  | 20.64  | 20.75  |
| AE12           | 17.95  | 17.98  | 18.08  |

Table 7. Types of Different Materials and Results of Electric Potential for FFE.

| Type of Sensor | PZT-5H | ZnO    | A/N    |
|----------------|--------|--------|--------|
| AE1            | 2.45   | 0.02   | 0.05   |
| AE2            | 2.66   | 0.03   | 0.08   |
| AE3            | 2.66   | 0.04   | 0.08   |
| AE4            | 3.21   | 0.04   | 0.10   |
| AE5            | 3.55   | 0.05   | 0.09   |
| AE6            | 3.56   | 0.06   | 0.10   |
| AE7            | 3.76   | 0.07   | 0.11   |
| AE8            | 3.88   | 0.07   | 0.10   |
| AE9            | 4.02   | 0.08   | 0.11   |
| AE10           | 5.36   | 0.08   | 0.12   |
| AE11           | 5.95   | 0.09   | 0.12   |
| AE12           | 7.34   | 0.09   | 0.13   |

Table 8. Types of Different Materials and Results of Electric Potential for FBE.

| Size of Sensor | PZT-5H | ZnO    | A/N    |
|----------------|--------|--------|--------|
| AE1            | 2.75   | 0.04   | 0.10   |
| AE2            | 3.22   | 0.05   | 0.10   |
| AE3            | 3.46   | 0.06   | 0.11   |
| AE4            | 3.98   | 0.06   | 0.13   |
| AE5            | 4.71   | 0.07   | 0.12   |
| AE6            | 5.89   | 0.07   | 0.12   |
| AE7            | 5.68   | 0.07   | 0.13   |
| AE8            | 5.02   | 0.07   | 0.12   |
| AE9            | 4.24   | 0.08   | 0.14   |
| AE10           | 4.20   | 0.09   | 0.13   |
| AE11           | 4.43   | 0.09   | 0.12   |
| AE12           | 4.88   | 0.10   | 0.12   |
Figure 6. Comparison results of resonant frequency between different materials at FFE.

Figure 7. Comparison results of resonant frequency between different materials at FBE.
5. Conclusions
In this paper, the materials used to simulate beams for resonators in AE detection show a positive result for generating the high resonant frequency of mechanical vibrations. The main focus is to design the sensor with high vibration frequency to easily match with the target for AE which is a range of 10 kHz - 300 kHz. The analysis of the eigen frequency helped to determine the resonant frequency and electric potential of the cantilever beam. Among of this selection material which is PZT-5H, ZnO, and AlN show that the most suitable piezoelectric layer is ZnO due to it is suitable enough for AE technique, environmentally friendly which is free pollution is used in order to support green technology compared to others material discussed and might generate high frequency for the sensor to detect PD signals.

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