Finite element analysis on the quartz plate due to the placement of quartz crystal microbalance on printed circuit board

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Abstract. Quartz Crystal Microbalance (QCM) is a high sensitivity piezoelectric sensor that enables it to detect loads in the nanogram order. QCM usually consists of a thin quartz plate with an AT-cut orientation. The sensor resonance frequency and its stability are affected by the sensor parameter and its placement in the reaction cell. Previous studies have shown that the physical parameters and geometric shapes of the QCM sensor greatly affected the sensitivity and stability of the sensor. As the sensor is thin, only in the order of hundredths micrometer, pressure, or force on top of the sensor surface also affects the sensor resonance frequency. In this study, we conducted a deformation analysis due to the placement of QCM on the Printed Circuit Board (PCB). The simulation is done by Finite Element Method using ANSYS 19.2. Variations in the shape of the electrodes on the PCB and O-ring elastic modulus that used in the QCM system has been investigated. O-rings that have a smaller elastic modulus will cause greater deformation. From the two types of PCB electrodes, electrodes in the form of ¾ circular arcs give smaller deformations than electrodes in the form of ½ circular arcs. The deformation occurs in the order of 10⁻⁶ m.

1. Introduction
Quartz Crystal Microbalance (QCM) is a high sensitivity piezoelectric sensor that is able to detect loads in a nanogram. QCM consists of a thin AT-cut quartz disk and electrodes located on each sensor surface [1]. Since it was developed in 1959 by Sauerbrey, QCM has become the most commonly used acoustic wave sensor in the field of industrial, medical and environmental monitoring [2,3].

The QCM as a piezoelectric sensor resonates by means of stress applied to the sensor surfaces caused by a potential difference across its electrodes. The vibration of the sensor was caused by the polarity change of the applied potential. Thus, it is obvious that any applied pressure on the sensor surface, which results in a force change on the sensor, may affect the sensor resonance. Some works show that the pressure change on the sensor surface results in a frequency change. The QCM sensor resonance frequency and its sensitivity to mass change were affected by a vacuum pressure [4] or high-pressure chamber [5]. Flow rate from a syringe pump [6] and peristaltic pump [7] affects the sensor resonance frequency, which may originate from the pressure change to the sensor. The stability of the sensor due to pressure change could be affected by the sensor parameter and installation of the sensor during the measurement setup.

Previous studies have shown that the physical parameters and geometric shapes of the QCM sensor greatly affected the sensitivity and stability of the sensor [8–10]. When scrutinized from quartz...
geometry, the sensitivity and stability of the sensor will be affected by the diameter, thickness, and orientation of the crystal cutting. The electrode diameter, shape, material and configuration affect the sensitivity and stability of the sensor. Therefore, studies related to the physical property and geometrical shapes of the sensor and electrode was conducted to investigate the mechanical and electrical behavior of the QCM sensor [8–12].

The design and development of QCM are often done experimentally. When conducting experiments, it is very difficult to avoid errors between experimental results and actual physical phenomena in QCM. Most methods for analyzing experimental results are limited to the 1-dimensional and 2-dimensional approaches. While in design, it is necessary to calculate according to the actual case, namely, with a 3-dimensional approach [13].

The current development of software simulation tools opens the opportunity to explore the QCM sensor behavior. For example, the application of Finite Element Analysis (FEA) can be a solution to create a QCM simulation space in actual physical phenomena. FEA is a numerical method that can be used to characterize the characteristics of complex structures accurately. That is very useful when used for the optimization of a microsystem design. In addition, compared to experiments, FEA can also save costs in QCM modeling and development [8,10]. Together with the powerful computer, the simulation can give a better understanding in a short time compared to the experimental works.

In its application, a QCM sensor is usually placed in the holder. The objective of the placement is to maintain the stability of the sensor and support the process of specimen injection to the sensor. In this study, we used cell construction and PCB as holders. Previous studies have discussed the influence of materials and geometries rather than quartz plates and electrodes. However, there are still little research that discusses the effect of different holder geometry and its physical properties on the QCM sensor system. The placement of the QCM sensor during the experiment may exhibit an unintended force to the sensor plate. The force can be evenly or unevenly distributed to the sensor surface.

In this study, we performed a deformation analysis on the quartz plate due to the placement of QCM on the PCB. Finite Element simulation is done by Static Structural analysis on ANSYS 19.2. The electrode geometry variation on the PCB and the O-ring elastic modulus used in the measurement system will affect the deformation of the quartz plate. In this research, we will look for the optimal PCB electrodes geometry and O-Ring elastic modulus as a QCM sensor holder.

2. Experimental

The QCM sensor setup was supposed to be placed on top PCB board. On top of the sensor disc, an O-ring was placed. The O-ring works to seal the liquid leakage when the sensor was closed with a reaction chamber. Figure 1 shows the sensor disc placement on the PCB. The bottom part (green) is the PCB; the yellow was a PCB track for electrical contact with the sensor electrode.

![Figure 1. The geometrical design of the QCM sensor system.](image-url)
Based on the configuration, stress analysis was done by using FEA on ANSYS Static Structural Analysis. The PCB track as contactor to the QCM electrode was configured as in Figure 2. The thickness of the PCB track was 40 \( \mu m \). Therefore, the sensor was placed as a circular cantilever. The load is applied to the top surface of the holder, which then goes to the O-ring and then to the sensor disc. The given load is 5 N for five seconds, with an additional load of 1 N per second. After finding out the most optimal design, we do a simulation with an uneven load on the O-ring, which will be analyzed for mechanical stability. Input variations are the geometry of PCB electrodes and the elastic modulus of the O-ring. O-ring elastic modulus variations used are 0.001 GPa, 0.005 GPa and 0.01 GPa. Quartz has a mesh with 195710 nodes and 99707 elements.

Figure 2. Electrodes geometry on PCB, (a) design A: \( \frac{3}{4} \) circular arcs and (b) design B: \( \frac{1}{2} \) circular arcs.

The materials used in this study are AT-cut quartz, sillicon rubber (O-Ring), PCB, acrylic (upper holder), and gold (Electrode). The dimensions of QCM are listed in Table 1. The quartz elastic modulus and piezoelectric constant are show in equation (1 – 2) [14]. The AT-cut orientation is cut with an angle of 35.25° to the z-axis [10].

\[
\begin{bmatrix}
    C_E \\ x \times \left(10^9 \text{ N/m}^2\right)
\end{bmatrix} =
\begin{bmatrix}
    86.48 & 7.04 & 11.91 & -18.04 & 0 & 0 \\
    7.04 & 86.48 & 11.91 & 18.04 & 0 & 0 \\
    11.91 & 11.91 & 105.55 & 0 & 0 & 0 \\
    -18.04 & 18.04 & 0 & 58.20 & 0 & 0 \\
    0 & 0 & 0 & 0 & 58.20 & -18.04 \\
    0 & 0 & 0 & 0 & -18.04 & 39.88
\end{bmatrix}
\]

(1)

\[
\begin{bmatrix}
    e \\ x \times \left(10^{-12} \text{ Cm}^2\right)
\end{bmatrix} =
\begin{bmatrix}
    0.171 & -0.171 & 0 & -0.041 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0.041 & -0.171 \\
    0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

(2)

Table 1. Dimensions of 10 MHz QCM.

| Name                  | Value (m)    |
|-----------------------|--------------|
| Quartz plate diameter | \(8.7 \times 10^{-3}\) |
| Quartz plate thickness| \(1.67 \times 10^{-4}\) |
| Electrode diameter    | \(4.5 \times 10^{-3}\) |
| Electrode thickness   | \(5 \times 10^{-8}\) |
3. Result and Discussion

3.1 Optimal design of PCB electrodes geometry
It's important to consider the mechanical strength of the quartz plate on the QCM sensor. The cutting orientation of the quartz plate will affect its resistance to compression. The range of resistance value of the quartz plate against compression is 2 – 3 GPa [14]. The deformation of quartz occurs from the beginning of the added load. In both designs, the deformation has the same pattern since the initial load increment, which looks like in Figure 3. From the deformation that occurs, it can be said if design A has smaller mechanical disturbances than design B. At 5 N load, the total deformation average in design A is $3.2977 \times 10^{-7}$ m and in design B is $3.0723 \times 10^{-6}$ m. Maximum stress intensity in design A is $1.0736 \times 10^8$ Pa and in design B is $4.0583 \times 10^8$ Pa, whereas the average stress intensity in design A is $3.1644 \times 10^6$ Pa and in design B is $1.1714 \times 10^7$ Pa. During the simulation, load and deformation have a linear relationship, and also the stress intensity value of those simulations is still below the value of resistance to compression. It shows that deformation occurs in the elastic area. This result could be attributed to the fact that in design A, the portion of the quartz disc which was hanging was smaller than design B.

![Figure 3](image-url)

**Figure 3.** Total deformation of the system with an O-ring elastic modulus of 0.001 GPa at 5 N load, (a) PCB design A and (b) PCB design B.

3.2 Optimal O-ring elastic modulus
Next, we look for the optimum elastic modulus of the O-ring for use in design A. In general, silicon O-rings have a modulus of elasticity in the range of 0.001 GPa to 0.05 GPa. We took three samples in this range, which are 0.001 GPa, 0.005 GPa, and 0.01 GPa. Based on the simulation that has been done, the greatest quartz mechanical disturbance occurs in the QCM system with silicone O-ring which has the smallest modulus of elasticity. The total deformation average in the design is $3.2977 \times 10^{-7}$ m and the maximum total deformation is $2.4529 \times 10^{-6}$ m. Conversely, the best design is found on silicon O-rings with the biggest modulus of elasticity because it has the smallest mechanical disturbance. The total deformation average in the design is $3.2093 \times 10^{-7}$ m and the maximum total deformation is $2.3739 \times 10^{-6}$ m. All variations of the O-ring elastic modulus that have been used give the same deformation pattern as in Figure 3a.

3.3 Uneven load analysis.
After finding out the most optimal design (Design A and O-ring elastic modulus 0.01 GPa), then we do the deformation analysis with uneven loads to find out the stability of the system. When conducting experiments, uneven loads can be caused by differences in the reaction cell wall surfaces that are in contact with the O-Ring in different cell constructions. The total load is the same as used in the previous
simulation, but the load is directly applied to the O-Ring. The load is divided into four parts as in Figure 4.

Figure 4. Uneven load input on the O-ring.

Figure 5. Total deformation of the optimum system with uneven load at 5 N.

In the first simulation, the load distribution at points D, E, and G respectively 20%, and at point, F was 40%. The results of the simulation can be seen in Figure 5. The total deformation, in this case, has a slightly different pattern from the previous input. Maximum total deformation is $2.9934 \times 10^{-6}$ m and average total deformation is $3.9303 \times 10^{-7}$ m. The average total deformation has a difference of $7.21 \times 10^{-8}$ m with the previous simulation. Whereas the maximum stress intensity in this simulation is $1.6064 \times 10^8$ Pa. The stress intensity value is still under the resistance value of the quartz plate against compression. From these results, it can be said that the optimal design has good mechanical stability against different load inputs. To find out how the influence of the overall geometry on the sensitivity and stability of the QCM sensor accurately, it is still necessary to do a modal analysis and harmonic response that can provide information about changes in the resonant frequency and the impedance characteristics of the QCM due to placement on the holder.

4. Conclusion
The 3D finite element analysis has been performed on the quartz plate due to the placement of QCM on PCB. The static structural analysis of the QCM sensor shows that the PCB track geometry affects the sensor deformation. PCB circular track with $\frac{3}{4}$ circle electrode, has a smaller deformation compared to the PCB with $\frac{1}{2}$ circle electrode. The O-ring with higher elastic modulus has a smaller disturbance to the sensor. In addition, the uneven force applied to the sensor disc affect the sensor deformation.
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References

[1] Arnau A 2008 *Piezoelectric transducers and applications* ed A A Vives (Berlin, Heidelberg: Springer Berlin Heidelberg)
[2] Wang R and Li Y 2013 *Biosens. Bioelectron.* 42 148–55
[3] Botha J A, Ding W, Hunter T N, Biggs S, Mackay G A, Cowley R, Woodbury S E and Harbottle D 2018 *Colloids Surf.A* 546 179–85
[4] Kashan M A M, Kalavally V, Mazumdar P, Lee H W and Ramakrishnan N 2017 *IEEE Sens. J.* 17 5044–9
[5] Wu Y T, Akoto-Amoakw A, Elbaccouch M, Hurrey M L, Wallen S L and Grant C S 2004 *Langmuir* 20 3665–73
[6] Ikhsani R N and Sakti S P 2017 Flow rate effect of syringe pump on quartz crystal microbalance sensor resonance frequency stability *Proceeding - 2016 International Seminar on Sensors, Instrumentation, Measurement and Metrology, ISSIMM 2016*
[7] Pratiti R A, Akbar M A and Sakti S P 2020 *J. Phys. Conf. Ser.* 1465 012003
[8] Wu D H, Tsai Y J and Yen Y T 2003 Robust design of quartz crystal microbalance using finite element and Taguchi method *Sensors Actuators B. Chem.* 92 337–44
[9] Lu F, Lee H P and Lim S P 2003 Finite element modeling and analysis of multi-channel quartz crystal microbalance *IEEE* 888–92
[10] Lu F, Lee H P, Lu P and Lim S P 2005 *Sensors Actuators A Phys.* 119 90–9
[11] Castro P, Resa P and Elvira L 2012 Apparent negative mass in QCM sensors due to punctual rigid loading *IOP Conf. Ser. Mater. Sci. Eng.*
[12] Sun H, Lu P, Zhang P and Chen H 2004 Dynamic analysis of AT-cut quartz resonators with ANSYS *IEEE* 1 95–8
[13] Jiang H 2009 Finite element analysis on electrode structure of QCM *IEEE* 3618–21
[14] Gautschi G 2002 *Piezoelectric Sensorics* (Springer-Verlag Berlin Heidelberg)