A Development of a Coarse Particle Concentration Measurement System Using a Crystal-Based Sensor and a Dust Sensor for Air Quality Measurement

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Abstract *- QCM or quartz crystal microbalance is a non-static crystal that can be used as a mass sensor. As a piezoelectric crystal, a QCM generates an electrical signal with a specific frequency. The frequency change can be utilized as a frequency counter in a mass measurement system. This study aims to develop a coarse particle sensor system using a QCM and an oscillator circuit. In line with this, this study uses an oscillator circuit and a QCM for sensor development. Thus, the frequency measurement of the QCM contains an oscillator and a signal conditioner connected to a microcontroller. For this purpose, an Arduino Nano was used as the signal processing, while a QCM was used as a coarse particle sensor and compared to a digital dust sensor (Winsen ZH03). The sensor system was evaluated using a fixed-type crystal connected to an oscillator: 2.5 MHz - 7.2 MHz. Arduino Nano processed the frequency signal generated by the developed oscillator. The results show that the sensor system has a stable output signal compared to the comparator. There is a linear correlation between the frequency measured by the system and the oscilloscope (99.73%). It can be concluded that the sensor system can measure coarse particle concentrations from 32-620 ug/cm*^{3} *(frequencies from 2 MHz to 7.2 MHz) with a response time of 1 second. The system has an accuracy of 99% and a resolution of 1 Hz.*

Keywords: *Coarse Particle; Dust Sensor; Frequency; Oscillator; Sensor System*

INTRODUCTION

Coarse particles are categorized as particulate matters with a diameter of <10 um. Coarse particle is bigger than fine and ultrafine particle (Wardoyo & Budianto, 2017; Wardoyo et al., 2020). The different size between coarse and fine-ultrafine particles make it easier for concentration detection. A spesific way to sense particulate matter concentration is by counting the mass using frequency shift or frequency change (Budianto et al., 2021).

Hertz (Hz) is the unit of frequency (*f*), the number of occurrences repeats per unit time in one full wave. Frequency is different with period (*T*). Period and frequency are inversely related. A period is the duration of time of the recurring event (Cerda, 2014). A resonator is a device that exhibits resonant behavior used to produce a specific frequency wave (Lombardi, 2002). One example of a resonator is a quartz crystal. Quartz crystal is a piezoelectric crystal that produces an electrical signal with a specific frequency (Mardiana et al., 2023; Putri et al., 2023). However, quartz crystals cannot generate frequency waves, so an oscillator is needed. An oscillator is an electronic circuit that can generate a periodic electrical signal with a constant amplitude. The oscillator circuit will convert a direct signal from a DC (direct current) voltage into an AC (alternating current) signal (Cerda, 2014). The oscillator will later produce a particular waveform at a specific frequency and amplitude over a period of time (Wu et al., 2022). There is a series of oscillators known as quartz crystal oscillators. A quartz crystal oscillator is an electronic oscillator circuit that uses mechanical resonance from a quartz crystal vibrating from a piezoelectric material to produce an electrical signal with the right frequency (Gobato, 2019). Quartz crystal oscillator consists of several types, one of which is used in this study is the Pierce oscillator. The Pierce oscillator is a parallel resonant circuit widely used because of its simplicity. The output signal of this oscillator produces a stable frequency and does not widen (Lee et al., 2013).

The frequency measurement method is essential to characterize the frequency oscillations. Some frequencies can be measured using traditional measurement methods. In the other side, frequency is a fundamental parameter in several snesing mechanisms, especially for particulate matter sensing using a piezobalance sensor. However, over time, the measured frequency is no longer simple and requires a method that utilizes technological sophistication. Traditional methods need more time to make accurate frequency measurements (Murrieta-Rico et al., 2018). Technological developments have led to new, more sophisticated, and modern frequency measurement methods. The frequency measurement of quartz crystals can be carried out using an oscilloscope and impedance analyzer, but both of these instruments offer quite expensive prices (Budianto et al., 2020, 2023).

Based on the description above, this study aims to develop a frequency-based coarse particle sensor system using an oscillator and an Arduino Nano microcontroller. Thus, the design is expected to easily measure the frequency with a low price and high performance.

RESEARCH METHODS

Sensor

The sensor system was developed using a QCM crystal (fundamental frequency = 5.00 MHz, purchased from PT Greatmicro, Indonesia). This crystal was used as a fixed coarse particle sensor (PM_{10}). For this purpose, the sensor was connected to an oscillator. The output signal from the oscillator was connected to a filter and a microcontroller. This system used a dust sensor ZH03 (Winsen) as a comparator device that measured coarse particle concentration (Fig. 1).

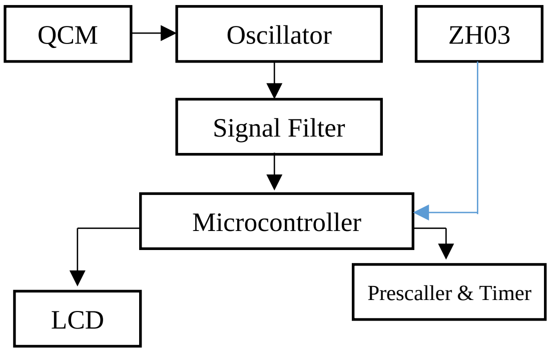

Figure 1. The schematic of the sensor system

Microcontroller

The microcontroller was programmed using Arduino IDE software. The signal processing was conducted when there was a signal from the sensor. The microcontroller will initialize the interrupt pin. The microcontroller has Timer 2 and Timer 5 which provides a time calculation (interval = 1 ms) and a prescaler value (128). These timers then were used as a signal converter (analog to digital converter - ADC) between 50 kHz and 200 kHz (Barański et al., 2019). Hence, the division clock value is 125 kHz.

After checking the ADC part, the microcontroller (pin D4) checked the sensor signal from the oscillator to count the frequency value (f) by comparing the period value (T). Equation (1) and (2) below show the calculation methods (Zhou et al., 2016):

$$T = \frac{t}{n} \quad (1)$$

$$f = \frac{1}{T} \quad (2)$$

Evaluation

The QCM inside a sensor box is connected to the oscillator to drive the quartz crystal to produce a frequency output signal. The signal from the oscillator is sent to the microcontroller for enumeration of the signal of the oscillator. The overall design of the hardware is packaged into a single unit in plastic packaging.

The sensing accuracy (*A*) was conducted by comparing the frequency value from the microcontroller and the comparators (an oscillator and a coarse particle concentration measurement system) (Widhowati et al., 2021). The %error value (in the unit of %) is obtained from the differences between frequency values from the sensor and the oscilloscope (Wen et al., 2015). Accuracy itself can be interpreted as the standard deviation (SD) from the mean value (Wen et al., 2015).:

$$A = 100\% - \%error \qquad (3)$$

RESULTS AND DISCUSSION

Results

a). Comparison Using an Oscilloscope

The digital oscilloscope was used in the system calibration to calibrate the oscillator's output frequency. The oscillator circuit test results can provide information regarding the stability and suitability of the output signal frequency (*f*) from the crystal within a certain time interval (*t*). The suitability of the frequency value produced by the oscillator compared to the fundamental frequency value of the quartz crystal can be observed in Table 1 below.

Table 1. Frequency (MHz)

No.	Fixed Crystal	Sensor System
1.	2.46 (crystal)	2.45
2.	3.58 (crystal)	3.58
3.	4.00 (crystal)	4.00
4.	**5.00 (QCM)**	**5.00**
5.	6.00 (crystal)	6.00
6.	7.20 (crystal)	7.19

Based on the sensor frequency calibration results in Table 1, it is known that the resulting standard deviation (SD) is very small ($p < 0.05$). It can be concluded that the sensor measures the crystal frequency from the oscilloscope with a stable characteristic. Table 1 also shows that the output signal of the sensor is similar to quartz crystal fundamental frequency (5 MHz).

b). Sensing Performances

The oscillator has good performance. Then the next step is to test the frequency measurement system by reading the oscillator's frequency signal output. The application of the frequency measurement system requires a microcontroller as a signal processing element to enumerate the output signal results.

Table 2. Coarse particle concentrations ($\mu g/m^3$)

No.	Sensor System (MHz)	ZH03
1.	4.46 (initial)	32
2.	4.18	150
3.	4.00	260
4.	3.87	410
5.	3.50	540
6.	3.42 (saturated)	620

At the testing stage, the frequency measurement system response also has the same stages as in the oscillator circuit testing stage, in which a crystal is used as the object being tested with variations in the previous crystal's basic frequency. The suitability of the frequency response produced by the system using a QCM compared to the ZH03 sensor (Table 2). It can be seen that there is a significant correlation between the measured concentrations and QCM's frequencies ($R^2 > 0.98$).

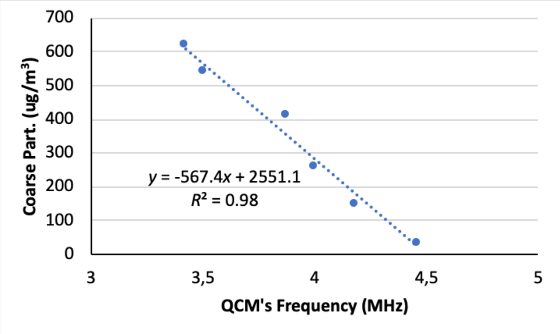

Figure 2. Sensor's responces under different coarse particle concentrations

Discussion

Based on the results of the frequency measurement system response test (Fig. 2), it can be seen that the correlation coefficient is 0.98, whose value is close to one ($R^2 = 1$). According to a previous study (Eeftens et al., 2016), it is the result of test data with perfect linearity. The result also shows that the frequency value is still quite accurate because the standard deviation is very small. However, there is an offset value spike in SD value at the 8 MHz frequency. This result is due to the capability of the microcontroller, which has a maximum reading frequency under the used prescaller.

The oscillator circuit can work well, as proven by the test results (Fig. 2). According to the results, the oscillator has a fairly wide measurement range, > 2 MHz. The measurement range of the Pierce oscillator is close to research conducted by Lee (Lee et al., 2013). In addition, other parameters indicate that the oscillator can function properly. However, the accuracy of the oscillator is an important parameter too. It can be concluded that the oscillator design can function very well and be applied in this study.

The accuracy of the oscillator circuit depends on the transistors and IC (integrated circuit) chips, resistors, and other passive components (Gobato, 2019). The used IC, as an active electronic component, is a single component with a complex semiconductor materials (such as silicon). The quality of the IC chip might influence the signal quality of the oscillator circuit, including the harmonic signal and the value of *t* (sampling time and prescaller time), amplitude *a*, and the impedances, *Z* (Cestnik et al., 2022; Rinaldi & Fauzi, 2019). A better IC quality will generate a better signal (Sakti, 2014). Thus, as explained in a previous study, the use of an IC chip in an oscillator circuit (combined with a microcontroller) has a high and good signal with a resolution of 2 kHz (accuracy = >90%) (Mardiana et al., 2020). This previous study indicates that the use of an IC chip has a moderate resolution. Compared to the resulting data from this study, it can be seen that the addition of a prescaller can generate a better resolution, 1 Hz.

In addition, the designed system has a good resolution of 1 Hz and a response time of 1 second. This statement follows the research conducted by Sakti (Sakti, 2014), which states that a resolution of 1 Hz every second will produce high sensitivity and be able to condition the stability of the frequency measurement system during the measurement period. From the explanation above, it can be concluded that the overall system design works well and can be developed for further research.

CONCLUSION

It can be concluded that the sensor system works well in sensing and measuring coarse particle concentrations combined with the ZH03 sensor (from Winsen). The optimum frequencies are 2 MHz to 7 MHz, with the response time of 1 s. The detected coarse particle concentrations are 32-620 as the measurement range. It can be recommended as a good sensor for the air quality measurement, especially for particulate matter measurement. This system can be further developed using a faster microcontroller board (such as a 32 bit microcontroller) to obtain a better signal. The use of a faster microcontroller can also generate a smaller resolution with a wider range and a higher accuracy level.

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REFERENCES

Barański, R., Galewski, M. A., & Nitkiewicz, S. (2019). The Study of Arduino Uno Feasibility for DAQ Purposes. Diagnostyka, 20(2), 33–48. https://doi. org/10.29354/diag/109174.

Budianto, A., Ponco Wardoyo, A. Y., Masruroh, Dharmawan, H. A., & Nurhuda, M. (2020). A Study of the Correlation Between Fine Particle Mass Loading Effect and Frequency Shift of a Bare QCM. AIP Conference Proceedings, 2296(November). https://doi.org/10.1063/5.0030820.

Budianto, A., Wardoyo, A. Y. P., Masruroh, M., Dharmawan, H. A., & Nurhuda, M. (2021). Performance Test of an Aerosol Concentration Measurement System Based on Quartz Crystal Microbalance. Journal of Physics: Conference Series, 1811, 1–8. https://doi.org/10.1088/1742-6596/1811/1/ 012033.

Budianto, A., Wardoyo, A. Y. P., Dharmawan, H. A., Hadi, K. A, & Mardiana, L. (2023). Graphene Oxide-Coated Quartz Crystal Microbalance for Bioparticle Detection (A Case Study for *Bacillus sp*.). Evergreen, 10(01), 155–161.

Cerda, R. M. (2014). Understanding Quartz Crystals and Oscillators (Unabridge). Norwood: Artech House Publisher.

Cestnik, R., Mau, & Rosenblum, M. (2022). Inferring Oscillator's Phase and Amplitude Response From a Scalar Signal Exploiting Test Stimulation. New Journal of Physics, 24, 123012.

Eeftens, M., Meier, R., Schindler, C., Aguilera, I., Phuleria, H., Ineichen, A., Davey, M., Ducret-stich, R., Keidel, D., Probst-hensch, N., Künzli, N., & Tsai, M. (2016). Development of Land Use Regression Models for Nitrogen Dioxide, Ultrafine Particles, Lung Deposited Surface Area, and Four Other Markers of Particulate Matter Pollution in the Swiss SAPALDIA Regions. Environmental Health, 1–14. https://doi.org/10.1186/s12940-016-0137-9.

Gobato, R. (2019). Rhodochrosite as Crystal Oscillator. American Journal of Biomedical Science & Research, 3(2), 187–187. https://doi.org/10.34297/ajbsr.2019.03.000659.

Lee, K. K., Granhaug, K., & Andersen, N. (2013). A Study of Low-Power Crystal Oscillator Design. Norchip, 1, 4–7. https://doi.org/10.1109/NORCHIP.2013.6702036

Lombardi, M. A. (2002). Fundamentals of Time and Frequency. In The Mechatronics Handbook (pp. 17-1-17–18). https://doi.org/ 10.1201/9781420037241.ch10.

Mardiana, L., Wardoyo, A.Y.P., Masruroh, M., & Dharmawan, H.A. (2020). Identification of the Relationship of Carbon Dioxide Concentration and the Frequency Changes of a Quartz Crystal Microbalance (QCM) Oscillation Sensor as a Preliminary Study of a Carbon Dioxide Gas

Sensor. AIP Conference Proceedings, 2296, 020119.

Mardiana, L., Wardoyo, A. Y. P., Masruroh, M., & Dharmawan, H. A. (2023). A Study of an n-TiO_2 Coated QCM Sensor's Response and Reversibility under CO_2 Exposure. Polish Journal of Environmental Studies, 32(2), 1735–1742.

Murrieta-Rico, F. N., Sergiyenko, O. Y., Petranovskii, V., Hernandez-Balbuena, D., Lindner, L., Tyrsa, V., Tamayo-Perez, U. J., & Nieto-Hipolito, J. I. (2018). Optimization of Pulse Width for Frequency Measurement by the Method of Rational Approximations Principle. Measurement: Journal of the International Measurement Confederation, 125(April), 463–470. https://doi.org/10. 1016/j.measurement.2018.05.008.

Putri, N. P., Suaebah, E., Rohmawati, L., Santjojo, D. J. D. H., Masruroh, & Sakti, S. P. (2023). Implications of the Electrodeposition Scan Rate on the Morphology of Polyaniline Layer and the Impedance of a QCM Sensor. Trends in Sciences, 20(3). https://doi.org/10.48048/ tis.2023.6411.

Rinaldi, R. G. & Fauzi, A. (2019). A Complete Damped Harmonic Oscillator Using an Arduino and an Excel Spreadsheet. Physics Education, 55, 015024. https://doi.org/10.1088/1361-6552/ab539d.

Sakti, S. (2014). Dual Channel High Precision 26 Bit Frequency Counter Using CPLD XC95108XL for QCM Sensor System. International Journal of Information and Electronics Engineering, 4(3), 239–243. https://doi.org/10.7763/ijiee.2014.v4.441.

Wardoyo, A., & Budianto, A. (2017). A DC Low Electrostatic Filtering System For $PM_{2.5}$ Motorcycle Emission. IEEE Xplore, 1, 51–54.

Wardoyo, A. Y. P., Dharmawan, H. A., Nurhuda, M., & Budianto, A. (2020). A High Voltage Electrostatic Filter for Particulate Matter $PM_{2.5}$ Capture Applied in Motor Vehicle Exhaust System. Journal of Physics: Conference Series, 1528(1). https://doi.org/10.1088/1742-6596/1528/ 1/012001.

Wen, H., Xiao, Z., Markham, A., & Trigoni, N. (2015). Accuracy Estimation for Sensor Systems. IEEE Transactions on Mobile Computing, 14(7), 1330–1343. https://doi.org/10.1109/TMC.2014.23 52262

Widhowati, A. A., Wardoyo, A. Y. P., Dharmawan, H. A., Nurhuda, M., & Budianto, A. (2021). Development of a Portable Volatile Organic Compounds Concentration Measurement System Using a CCS811 Air Quality Sensor. IEEE Xplore, 1–5. https://doi.org/10.1109/ISESD530 23.202 1.9501642

Wu, J., Yan, Y., Hu, Y., Qian, X., & Zheng, G. (2022). Oscillation Frequency Measurement of Gaseous Diffusion Flames Using Electrostatic Sensing Techniques. Fuel, 311(April 2021), 122605. https://doi.org/10. 1016/j.fuel.2021.122605

Zhou, H., Melloni, L., Poeppel, D., & Ding, N. (2016). Interpretations of Frequency Domain Analyses of Neural Entrainment: Periodicity, Fundamental Frequency, and Harmonics. Hypothesis and Theory, 10(June), 1–8. https://doi.org/ 10.3389/fnhum.2016.00274