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Impedance Measurement of the Quartz Crystal Microbalance using Phase Gain Detector and Digital Storage Oscilloscope

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Abstract. Quartz Crystal Microbalance (QCM) sensor responds measurement can be done in three different methods. One method which gives a rich information is the impedance measurement of the QCM sensor using a phase gain measurement. In this configuration, the QCM sensor was placed in a configuration where the sensor was injected with a sinusoidal signal. Signal gain and phase difference between the signal before and after the QCM sensor was measured and compared. An integrated circuit which able to measure the gain and phase difference is available in a low cost and small footprint. In other hand, the high-performance digital oscilloscope is also available in the market with reasonably priced. In this experiment, we comparing the use of the AD8302, gain and phase detector circuit, and Picoscope 5244B. Picoscope 5244B is a high-performance Digital Storage Oscilloscope (DSO). The result showed that the AD8302 gave an easy and direct results of the gain and phase value. The output can directly processed using a microcontroller which allow for the development of a gain and phase detection system. In other hand, the DSO provided a true signal comparison between the input signal and output signal, but it required a complex processing.

1. Introduction

The utilization of Quartz Crystal Microbalance (QCM) sensor has exponentially extent in numerous fields, especially in chemical and biological study. Since the first introduction of this device in 1959 [1], researchers developed many aspects of the fundamental and applications of the QCMs. Focus was not only to the sensor structure, surfaces or coating layers but also through advancing their interfacing circuits to obtain more sophisticated measurement and to explore the possibilities to get more information from the measurement.

Quartz Crystal Microbalance response measurement can be done using a frequency measurement, dissipation signal and also impedance measurement [2]. Among many methods, the electrical impedance is one of the preferred analysis. The method provides rich information. Each of the methods has its own advantages and limitation. Impedance of the QCMs defines the QCM behavior acting under the senses. The impedance measurement can lead us to investigations of material properties, such as complex shear modulus[3], viscosity [4–7] and loading effect caused by coatings on QCM's surface [8]. Nevertheless, the need of relatively expensive instrument for the measurement might be inevitable. The complexity in processing is one of the main reasons.

In the impedance measurement, a sinusoidal signal (input signal) is injected into the circuit containing the element under test. The signal before the circuit is the input signal and the signal after the circuit is the output signal. Calculation of the impedance was done by comparing the input signal



and output signal by considering the circuit configuration [9]. In this experiment, we used a simple voltage divider circuit with a known resistive element. Impedance value and phase were calculated based on the measurement of the signal using a phase gain integrated circuit detector and digital storage oscilloscope.

A phase gain integrated circuit detector is widely used as the magnitude and phase measurement. In many applications, this device has been utilized in order to acquire information which benefit the research to explain more phenomenon. For example, it can be used for the superheterodyne microwave interferometer [10] and for bioimpedance spectra of tissues [11]. Based on the device, the magnitude and phase are resulted from analog AC voltage signals. Consequently, the device would also be potential to measure the QCM impedance with some modified circuits before detected by the device.

The phase gain integrated circuit detector takes two signals as inputs and results in two DC output signals proportional to the ratio of the magnitudes ratio and the phase difference of the two signals. The detector usually detects inputs in a specific frequency range. For instance, AD8302 (Analog Devices, USA) can only detect and process RF/IF inputs. The device would probably be made for detecting low-frequency signals if some modification was conducted in the input circuit [11]. The resonance frequency of the typical QCM sensor was ranging from 5MHz to 20MHz. This range is well suited into the detected range of the AD8302.

The DSO is now widely available. With the advancement in microelectronic technology, a DSO with a sampling rate of up to GHz and data storage up to Gigabyte is available. There are two main advantages of using the DSO as an instrument for signal measurement. Firstly, the data measured can automatically be stored in a personal computer which provided an easy way for further processing. Secondly, the DSO is commonly commercialized with an ability of measuring AC inputs in several channels, usually in two or four channels. Therefore by using the recorded signal which was measured in the same time, gain and phase shift can be calculated.

In this experiments, we compared two measurement method of the electrical impedance of a QCM sensor around its series resonance frequency. The AC signal source was a direct digital signal generator, AD-9910. We showed that by using a best fitting processing stage, we eliminated the instability of the signal generator.

2. Experimental

2.1. Material

The Quartz Crystal Microbalance (QCM) sensor was a 10MHz HC-49/U resonator purchased from PT Great Microtama Surabaya, Indonesia. The resistor reference was used an SMD resistor Vishay Thin Film. The resistance has the specification of resistance value of 50 Ω , tolerance of 0.1%, temperature coefficient of 25ppm and maximum power dissipation of 0.25W.

The gain phase measurement was done using an AD8320 circuit. The signal generator used a DDS AD-9910. The reference clock source used a 100MHz TCXO. The signal from the DDS was buffered using an operational amplifier (OPA-820).

2.2. Measurement setup

Many methods can be used for impedance measurement, such as null, resonance and active [12]. One of the simple methods is to utilize voltage and current (V-I) ratio in a closed-loop circuit [13,14]. Figure 3 shows the scheme of electronics circuit which is arranged for the measurement. The Device Under Test (DUT), the device whose impedance will be measured, symbolized as Z_X in this case, lies on the circuit in which an AC signal is passed through. The value of Z_X can be calculated based on the ratio of the V_1 and V_2 and the phase difference of both voltage at a given frequency. The ratio of the V_1 and V_2 and the phase different can be done using gain and phase detector AD8302 and based on the recorded voltage using DSO.

Based on the Figure 1, the voltage of the signal after passing the Z_X (QCM sensor) can be calculated by using Equation (1).

$$V_2 = V_1 \frac{R}{Z+R} \quad (1)$$

The impedance value of the Z can be calculated using Equation (2). The impedance value can be calculated based on the voltage ratio which is complex.

$$Z = \left(R \frac{V_1}{V_2} \right) - R \quad (2)$$

The impedance value ($|Z|$) was calculated directly using the absolute voltage ratio of the V_1 and V_2 , and the phase different is the phase shift is the phase different of the V_1 and V_2 .

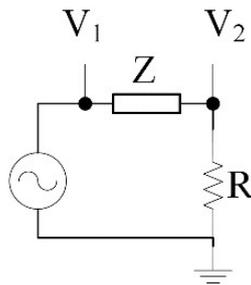


Figure 1. V-I method configuration.

Figure 2 shows the diagram of the measurement using the DSO and phase gain integrated circuit detector. The DSO recorded the sinusoidal signal before and after passed the QCM sensor. The AD8302 output voltage was acquired directly using a 10bit ADC of the microcontroller PIC18F45K50. Two output voltage of the AD8302 was converted and send directly to the personal computer. The frequency of the signal generator was manually set for each measurement with a frequency starting from lower frequency than the series resonance frequency of the QCM sensor and higher frequency with a frequency interval of 50Hz.

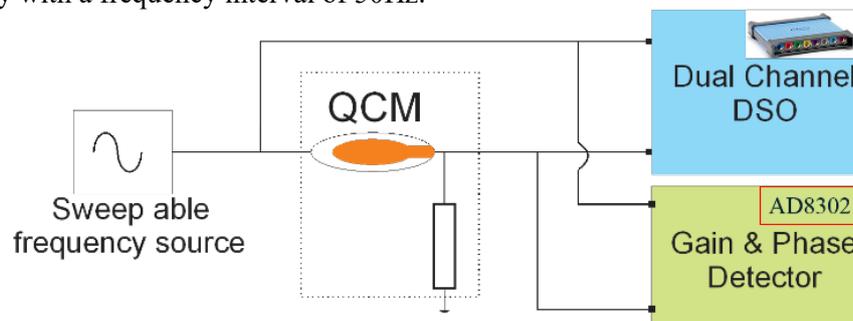


Figure 2. Measurement diagram

The QCM was modeled using the Butterworth-van-Dyke (BVD) equivalent circuit as presents in Figure 3 [15]. Based on the model, the system has a series resonant frequency (f_s) at minimum impedance and parallel resonant frequency indicates by a maximum impedance. Since work of the QCM sensor is commonly based on its series resonance frequency, impedance measurement around that point was importance. Therefore this experiment focused on the impedance measurement around the series resonance frequency.

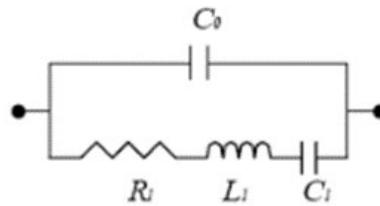


Figure 3. BVD model of the Quartz Crystal Microbalance

3. Result and Discussion

3.1. Impedance Measurement Using DSO

Sinusoidal signal of before the QCM sensor was measured using channel A (blue line) and the signal after the QCM sensor was measured using channel B (red line) of the DSO. The voltage range was set from -5V to +5V. Based on the resonance frequency measurement of the QCM sensor, the frequency range of the measurement was set from 9999500 Hz to 10001500 Hz, with an interval of 50 Hz. Figure 4a shows the recorded signal.

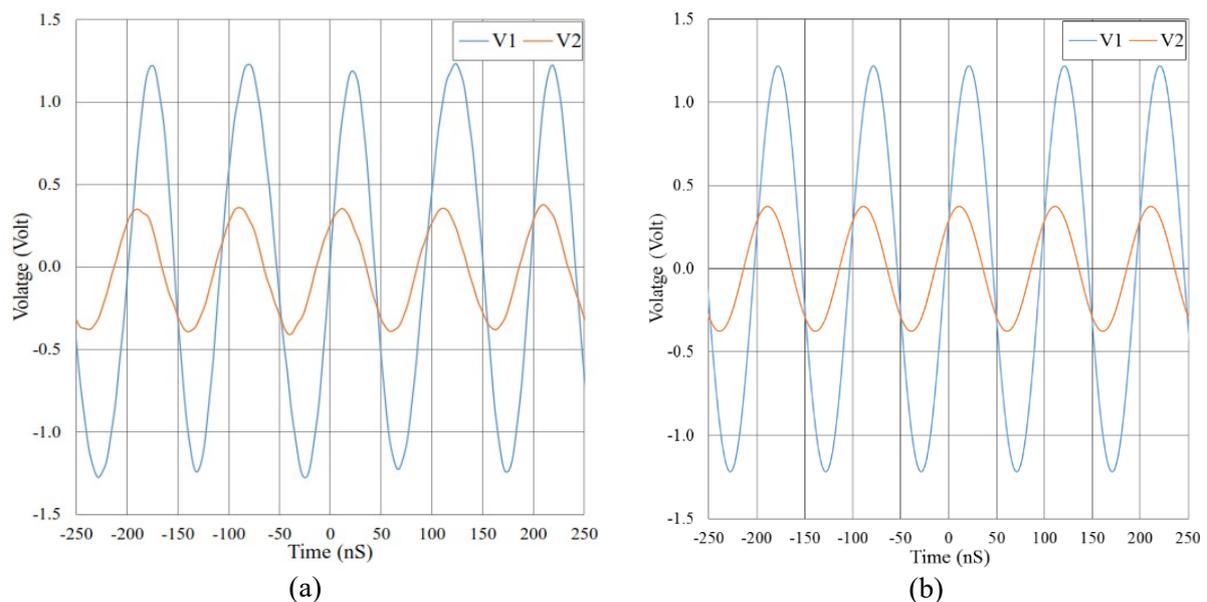


Figure 4. 2-channel waveforms of the Picoscope 5244B outputs at a frequency of 10001400Hz, (a) measured signal (b) best-fit sinusoidal model.

It can be seen from Figure 4a that the recorded signal was not stable sinusoidal signal. The signal does not represent a pure sinusoidal signal. It was also observed that the frequency and peak voltage of the signal varied slightly. Therefore, the outputs were fitted with a sinusoidal signal model by minimizing the error using Generalized Reduced Gradient (GRG) non-linear method in Excel. Figure 4b shows the fitted sinusoidal signal. It can be seen that the signal became a smooth sinusoidal signal. The absolute ratio of the input voltage and output voltage can be taken from the fitted model. The absolute impedance value was calculated using Equation (2).

The analysis using the Lissajous curve of the V_1 and V_2 showed the variation of the signal. Figure 5a shows the Lissajous curve of the V_1 and V_2 . Figure 5b shows the Lissajous curve of the sinusoidal

model of the measured signal. The original signal curve shows a multiline curve. It indicated that there was a slight variation of V_1 and V_2 . The multiline of the Lissajous curve shows that there is a signal variation both in the magnitude of V_1 and V_2 as well as in the phase difference between V_1 and V_2 . In contrast, the fitting model shows only a single Lissajous curve. The curve was a result of two pure sinusoidal signal with constant amplitudes and a fixed phase difference. Therefore for the DSO signal calculation, a pre-processing step was done by implementing the GRG non-linear method to get the best fit model of the sinusoidal signal. The ratio of the V_1 and V_2 , as well as the phase difference, was taken based on the Lissajous curved of the best fit sinusoidal model.

The phased different of the signal can be measured directly using the sinusoidal signal of using Lissajous curve. The phase different (θ) was calculated based on the curve using Equation (3)

$$\theta = \arcsin\left(\frac{x(t_0)}{A}\right) - \arcsin\left(\frac{y(t_0)}{B}\right) \quad (3)$$

In which x and y are respectively the x-axis and y-axis in the Lissajous graph, the displacement of signal A and B in this case, at the same time t_0 , and A and B are the amplitudes of each output voltage (V_1 and V_2).

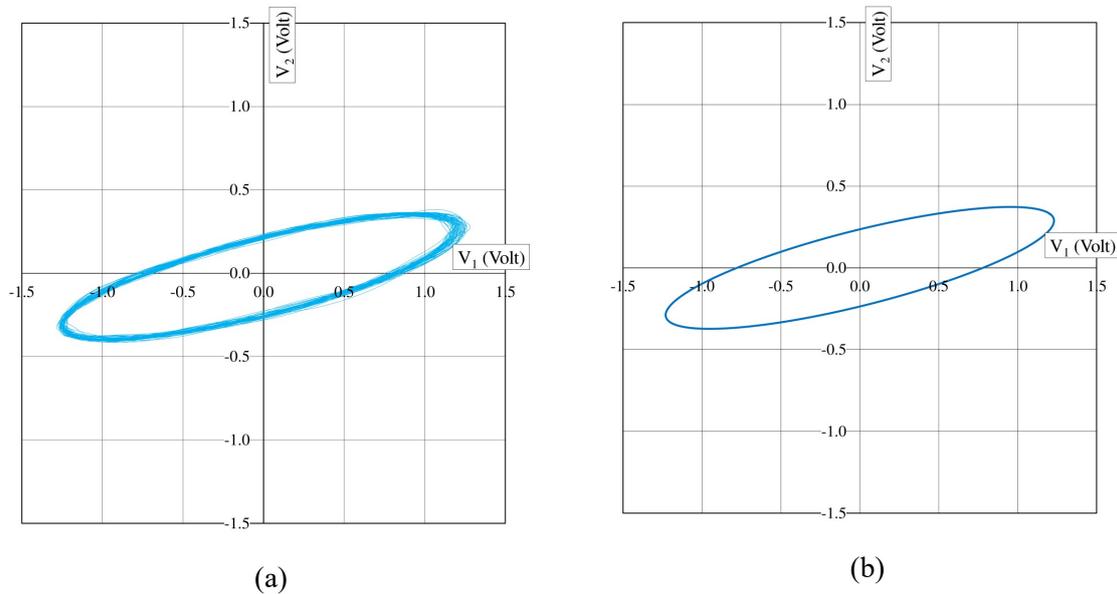


Figure 5. Lissajous curve of Signal A, from the input signal (V_1), over Signal B, after passed to the QCM (V_2), at a frequency 10001400Hz, (a) before and (b) after best-fit optimization.

3.2. Impedance Measurement Using Phase Gain Integrated Circuit Detector

The analysis of the phase gain integrated circuit detector is more straightforward than the DSO one. The amplitude ratio and the phase difference of the two input signals is processed in the AD8302. The values are presented as two DC output voltage as V_{mag} and V_{phase} . The impedance values and the phase differences were calculated using equation (4) and (5).

$$Z_2 = R \left(10^{\frac{(V_{mag}-0.9)}{0.6}} \right) - R \quad (4)$$

$$\theta = - \left(\left(\frac{0.9 - V_{phase}}{0.01} \right) + 90 \right) \quad (5)$$

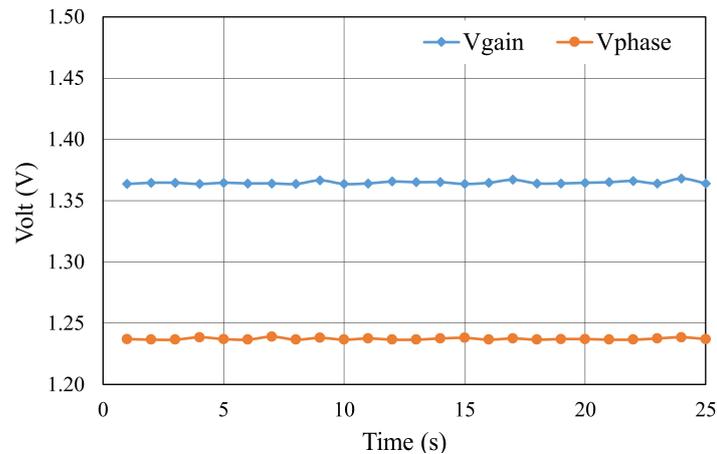


Figure 6. Output voltage of the gain and phase detector

It was observed that the V_{mag} and V_{phase} were varied. In the experiment, we measured 25 values of the phase and magnitude voltage for every given frequency. Figure 6 shows an example of the output voltage of the magnitude and phase difference of the AD-8302 in the experiment. The measured data showed that the variation of the phase and magnitude was less than 0.1%. The fact that the generated signal from AD-9910 was not constant, but having small variation [16], could be the source of the output voltage deviation. In addition, the non-perfectly sinusoidal signal generated by the DDS AD-9910 could also contribute the error. The voltage varied slightly showed that the signal source was not perfect. The results confirmed with the recorded signal using the DSO.

3.3. Comparison Between Impedance Measurement Using DSO and Using Phase Gain Integrated Circuit Detector

The absolute impedance value of the QCM Sensor under test is presented in Figure 7. It can be seen that the calculated impedance value from both method was not imposed one to the other. The calculated impedance using AD8302 was higher than the impedance value calculated using the DSO measurement. The calculated impedance calculated based on the DSO measurement has a closer value to a BVD model of the QCM sensor. It means that the accuracy of the DSO measurement using the DSO was better than the accuracy of the Gain Phase Detector. The DSO measurement showed a clear minimum impedance value of the QCM sensor at frequency around 10000500Hz. The measurement using the AD8302 had a minimum impedance value at the same frequency, but the value is hardly distinguished with the neighboring value.

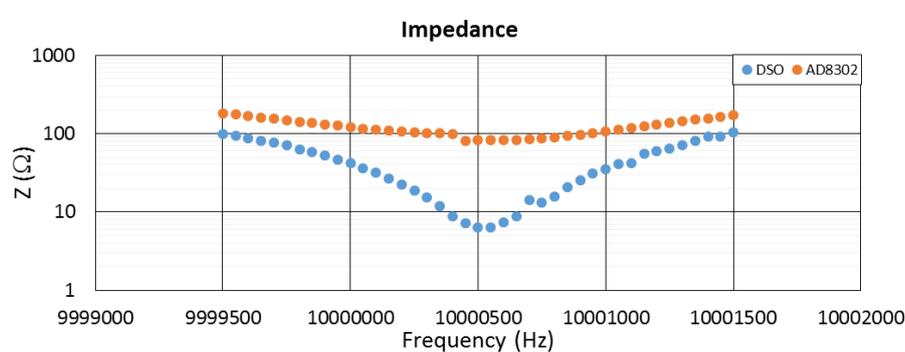


Figure 7. The plotted impedance spectrum resulted from DSO and phase gain integrated circuit detector (AD8302).

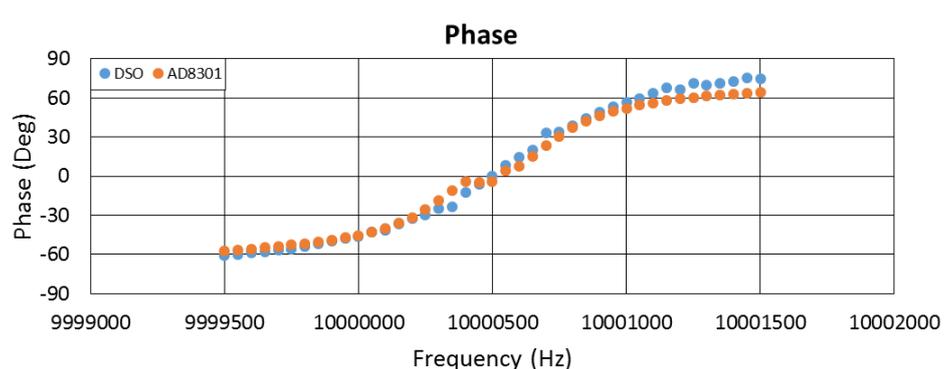


Figure 8. The plotted phase spectrum resulted from the DSO and phase gain integrated circuit detector (AD8302).

The phase value of the QCM sensor under test is depicted in Figure 8. Calculated phase of both measurement method has a similar results. Both of the calculated phase showed a zero phase at frequency at 10000500Hz. The value was in agreement with the frequency of the minimum impedance. The result was in agreement with the BVD model which indicated that the minimum impedance value of the QCM sensor occurs at zero phase. At zero phase the reactive part of the QCM model is Zero. Therefore the impedance value is only the resistive part of the BVD model of the QCM sensor.

4. Conclusion

The direct comparison between a Digital Storage Oscilloscope (DSO) and phase gain integrated circuit detector has been investigated. The gain phase detector required an averaging data for each measurements to reduce the signal source variations. The DSO provided more accurate results than the phase gain integrated circuit detector. The DSO required pre processing signal using best fit of a sinusoidal model to get a clear signal to be calculated. Despite this, the DSO required relatively complex processing to acquire impedance and phase result, and the phase gain integrated circuit detector simplified the measurement process.

Acknowledgement

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