DESIGN OF FREQUENCY OUTPUT PRESSURE TRANSDUCER

Jinge Ma

Thesis Prepared for the Degree of

MASTER OF SCIENCE

UNIVERSITY OF NORTH TEXAS

August 2015

APPORVED:

Hyoung Soo Kim, Major Professor
Haifeng Zhang, Committee Member
Yan Wan, Committee Member
Hualing Zhang, Committee Member
Shengli Fu, Chair of the Department of
Electrical Engineering
Costas Tsatsoulis, Dean of the College
of Engineering and Interim Dean
of the Toulouse Graduate School

Ma, Jinge. *Design of Frequency Output Pressure Transducer.* Master of Science (Electrical Engineering), August 2015, 48 pp., 2 tables, 39 illustrations, 28 numbered references.

Piezoelectricity crystal is used in different area in industry, such as downhole oil, gas industry, and ballistics. The piezoelectricity crystals are able to create electric fields due to mechanical deformation called the direct piezoelectric effect, or create mechanical deformation due to the effect of electric field called the indirect piezoelectric effect. In this thesis, piezoelectricity effect is the core part. There are 4 parts in the frequency output pressure transducer: two crystal oscillators, phase-locked loop (PLL), mixer, frequency counter. Crystal oscillator is used to activate the piezoelectricity crystal which is made from quartz. The resonance frequency of the piezoelectricity crystal will be increased with the higher pressure applied. The signal of the resonance frequency will be transmitted to the PLL. The function of the PLL is detect the frequency change in the input signal and makes the output of the PLL has the same frequency and same phase with the input signal. The output of the PLL will be transmitted to a Mixer. The mixer has two inputs and one output. One input signal is from the pressure crystal oscillator and another one is from the reference crystal oscillator. The frequency difference of the two signal will transmitted to the frequency counter from the output of the mixer. Thus, the frequency output pressure transducer with a frequency counter is a portable device which is able to measure the pressure without oscilloscope or computer.

ACKNOWLEDGEMENTS

First of all, I want to express my sincere thanks to my major professor Dr. Hyongsoo Kim and my co advisor Dr. Haifeng Zhang, for giving me such a precious opportunity to do the research. Dr. Kim showed me how to analyze and solve the problem as a professional engineer. Dr. Zhang's mechanical engineering knowledge helped me to view the problem at a different angle. I believe that all of these experiences will benefit me the whole life.

Secondly, I would like to show my appreciation and thanks to my thesis committee members, Professor Yan Wan and Professor Hualiang Zhang for their helps.

Next, I want to thank all of my lab mates for their help and discussion.

Finally, I would like to express my thanks to my family and friends, especially my girlfriend Jialing Song for her constant source of inspiration and support.

TABLE OF CONENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Background

Piezoelectricity effect is the property of certain solid materials, like crystals, certain ceramics and various proteins, in response to applied mechanical stress. The piezoelectric materials are able to create electric fields due to mechanical deformation called the direct piezoelectric effect, or create mechanical deformation due to the effect of electric field called the indirect piezoelectric effect.

Pierre Curie and Jacques Curie demonstrated the direct piezoelectric effect in 1880. They used tourmaline, quartz, topaz, and Rochelle salt as underlying crystal to test and predict their behavior. Finally, they proved the piezoelectricity effect. In 1881, Gabriel Lippmann deduce the indirect piezoelectric effect from fundamental thermodynamic principles and the Curies confirmed it.

In 1894 a German physicist, Woldemar Voigt, inferred that there were only 20 kinds of non-symmetry crystals have the piezoelectricity effect. In the First World War, an allied military scientist, P. Langevin, used the quartz transistor as a sonic transmitter to detect submarines. From then, people started to implement on piezoelectric effect in many areas such as: transducers, pressure sensors and piezoelectricity ceramics plate. Especially piezoelectric ceramics are widely used in microelectronics, bioengineering, and machine control to harvest energy.

1.2 Motivation

With the development of the modern technology, the piezoelectricity effect has been used increasingly and more widely in our daily life. It brings higher productivity and profit in several industries, including the gas industry and oceanography. The direct piezoelectric effect shows that when the crystal is mechanically strained or is deformed by the application of an external stress pressure, the resonance frequency will increase. This feature can be used to detect the relationship between resonance frequency change and external pressure.

Thus, using a crystal oscillator circuit is a good way to activate the piezoelectricity sensor and to transfer the signal to the signal process system. The Phase-locked loop (PLL) is a control system that constantly adjusts the output signal phase to match the phase of input signal. For getting the change of the resonance frequency, a frequency mixer is used. The output frequency of the PLL enters the port of the frequency mixer, at the same time; another reference piezoelectric sensor provides a stable frequency to the frequency mixer. As a result, the frequency mixer will generate a new frequency that is the difference between the two input frequencies. Consequently, the output of frequency mixer will be reflected upon the pressure changes.

This design is a perfect combination of the piezoelectricity effect and radio frequency technology. The pressure transducer provides a rugged sensor, which has wide dynamic range, high linearity, and high portability.

1.3 Overview of Thesis

This thesis includes several topics about the design and application of the pressure transducers. Among them, the piezoelectric effect and phase-locked loop are the most important parts. They are presented in the following chapters.

The second chapter begins with a discussion over the topic of piezoelectric effect and the principle of the piezoelectric material. Furthermore, testing data of piezoelectric crystal in pressure experiment is also presented in Chapter 2.

Chapter 3, the principle of the phase-locked loop is introduced. The fundamental design method includes phase detector working process, how the voltage control oscillator works and the waveform of the loop filter are presented. The phase-locked loop has a feedback loop where the voltage control oscillator signal can be automatically synchronized to the input signal.

Chapter 4, introduces the peripheral circuits around the piezoelectric crystal and PLL, such as the crystal oscillator circuit, which activates the piezoelectric crystal, and the mixer, which gets the difference from the pressure sensor and the reference crystal. The oscillator circuit has two inverters; one is used as a feedback system to activate the crystal, and the other one amplifies the oscillator output voltage to a level sufficient to drive the next stage circuit.

Chapter 5, presents all the implementation and the measurement of the design, including the waveform of the PLL circuit and the crystal oscillator circuit. The measurement result is the most persuasive way to prove the theoretical analysis and simulation.

At the end of the thesis, the last chapter concludes the whole design and presents the future possible uses of the piezoelectricity effect in different areas.

CHAPTER 2

PRINCIPLE OF PIEZOELECTRIC EFFECT

2.1 Introduction

Piezoelectric effect is a phenomenon of a solid material that under mechanical deformation can generate electricity. Piezoelectricity was found by Pierre Curie and Jacques Curie in 1880. Piezoelectric material can generate an electric field due to the mechanical deformation, electric field can also be caused by mechanical deformation field. This material have been used to make the smart structure, this kind of structure has self-bearing capacity, self-diagnosis, self-adaptation and self-repair functions. It will play an important role in aircraft design in the future.

Piezoelectric effect can be divided into direct piezoelectric effect and indirect piezoelectric effect. In direct effect, a positive voltage is generated across the surface when a poled piezoelectric material is subjected to external force in one direction. After the external force disappeared, piezoelectric material goes back to the uncharged state. The direction of the external force will change the polarity of charge. Using indirect piezoelectric effect of manufacturing can be used for acoustic transmitter and ultrasonic engineering. Fig 2.1 and Fig 2.2 show the whole process about how the piezoelectric effect works.

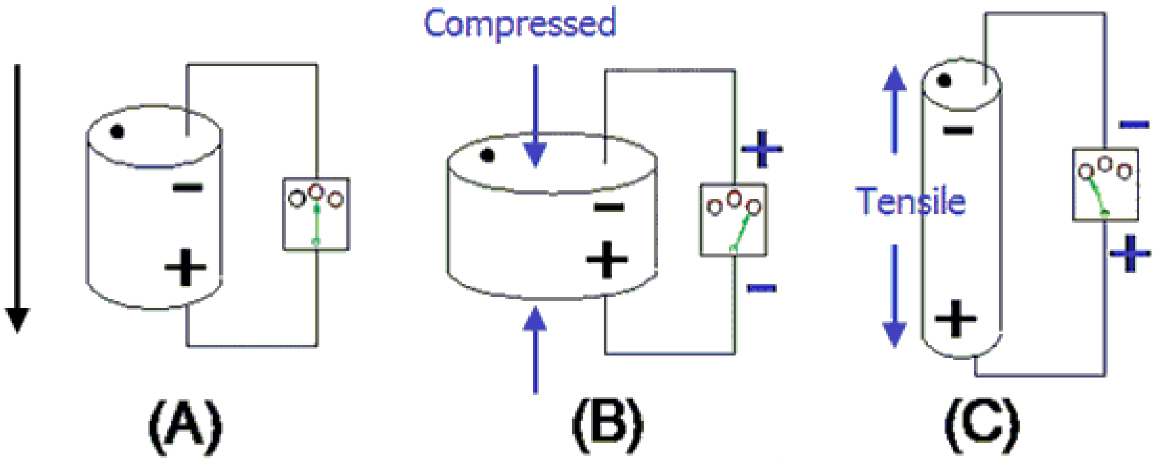


Fig 2.1 Direct piezoelectric effect

A) Piezoelectric material; B) When a compressive stress is applied to the material, voltage will be developed with the opposite polarity as the poling voltage; C) when tensile stress is applied to the material, voltage will be developed with the same polarity as the poling voltage and across the surface of the material.

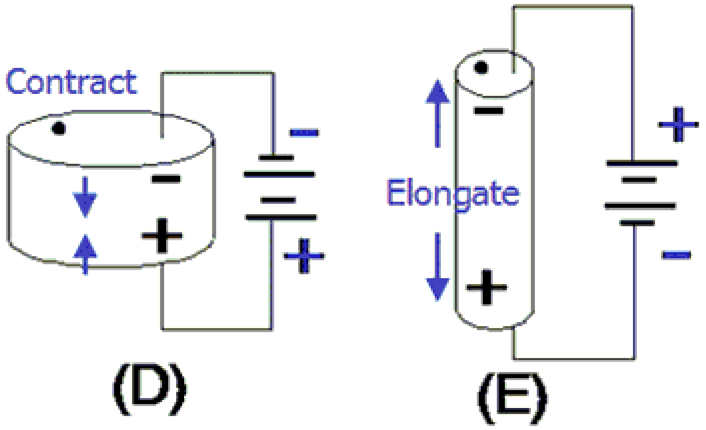


Fig 2.2 Indirect piezoelectric effect

D) When DC field is applied with the same polarity as the poling field, the compressive strain will be developed by the material; E) When the DC field is applied in opposite direction, the material develops tensile strain.

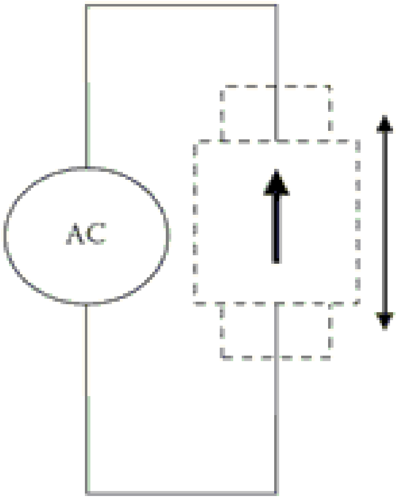


Fig 2.3 Piezoelectric material with AC field

AC field is applied to the piezoelectric material, the material vibrate producing an acoustic wave in the vicinity.

2.2 Piezoelectric Transducer Crystal

There are many application for crystals. They can be used to generate or sense various forms of strains like compression, shear, torsion, length and flexural vibrations. The design and production of transducer crystals depends on its application which is applied on acoustic items like wear plates and buffer rods. Furthermore, to get minimum sub-layer loss in fused silica and alumina, techniques such as high quality lapping and chemical overtone polish could be used.

2.2.1 AT-Cut Crystal

The AT-cut crystal is the most widely used cut and it is particularly used for electronic instrument. AT-cut is a cutting through parallel to the axis in a specific angle. AT-cut crystal is not sensitive to temperature.

2.2.2 Resonance Frequency

The resonance frequency of the AT-cut crystal F is:

$$f = \frac{n}{2d_Q}\left(\frac{c}{\rho}\right)^{\frac{1}{2}}$$

n: number of harmonics n=1, 3, 5….

d_Q: thickness of the Quartz crystal

c: coefficient of elastic shear

ρ: Quartz crystal density (2.65* 10^3 kg/m^3)

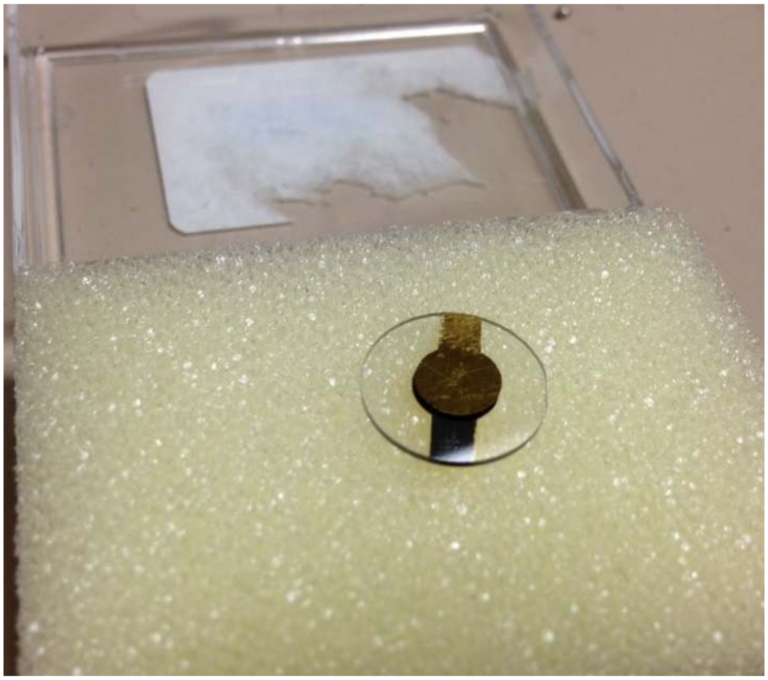


Fig 2.4 Piezoelectric crystal

2.3 Measure the Resonance Frequency

With the Bode analyzer, it is easy to get piezoelectric crystal in the frequency range from 1 Hz to 40 MHz.

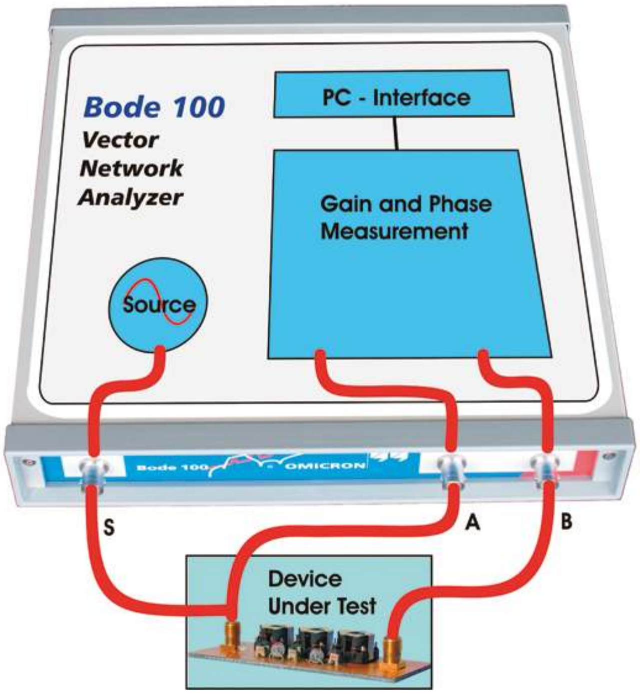


Fig 2.5 Diagram of the Bode analyzer

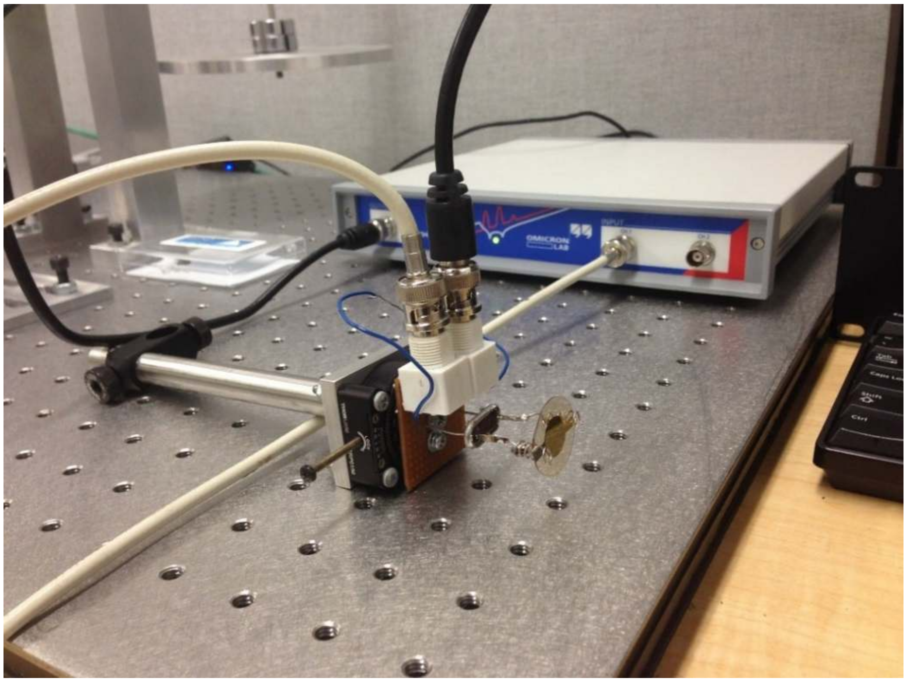
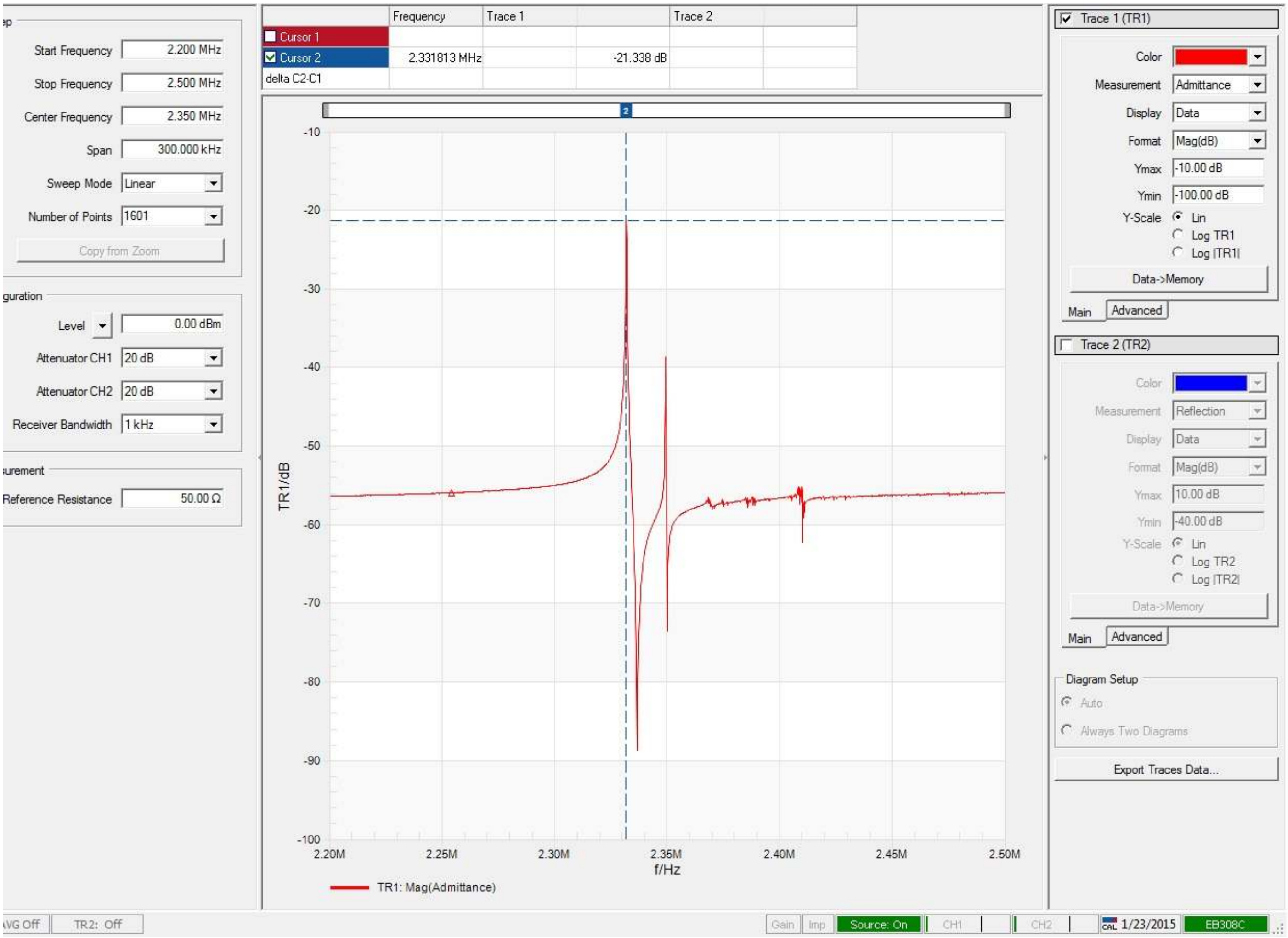


Fig 2.6 Bode analyzer with piezoelectric crystal

Sweeping the frequency from 1Hz to 40 MHz, the admittance waveform of the piezoelectric crystal is shown as Fig. 2.7



ep
Start Frequency 2.200 MHz
Stop Frequency 2.500 MHz
Center Frequency 2.350 MHz
Span 300.000 kHz
Sweep Mode Linear
Number of Points 1601

guration
Level 0.00 dBm
Attenuator CH1 20 dB
Attenuator CH2 20 dB
Receiver Bandwidth 1 kHz

urement
Reference Resistance 50.00 Ω

	Frequency	Trace 1		Trace 2	
☐ Cursor 1					
☑ Cursor 2	2.331813 MHz		-21.338 dB		
delta C2-C1					

☑ Trace 1 (TR1)
Color
Measurement Admittance
Display Data
Format Mag(dB)
Ymax -10.00 dB
Ymin -100.00 dB
Y-Scale ● Lin ○ Log TR1 ○ Log |TR1|

☐ Trace 2 (TR2)
Color
Measurement Reflection
Display Data
Format Mag(dB)
Ymax 10.00 dB
Ymin -40.00 dB
Y-Scale ● Lin ○ Log TR2 ○ Log |TR2|

Diagram Setup
● Auto
○ Always Two Diagrams

Fig. 2.7 Admittance waveform of piezoelectric crystal

2.4 Measurement of the Piezoelectric Effect

A balance is used to measure the piezoelectric effect. Hold the crystal in the balance and add the weight on the plate, changing of the frequency shown on the PC screen.

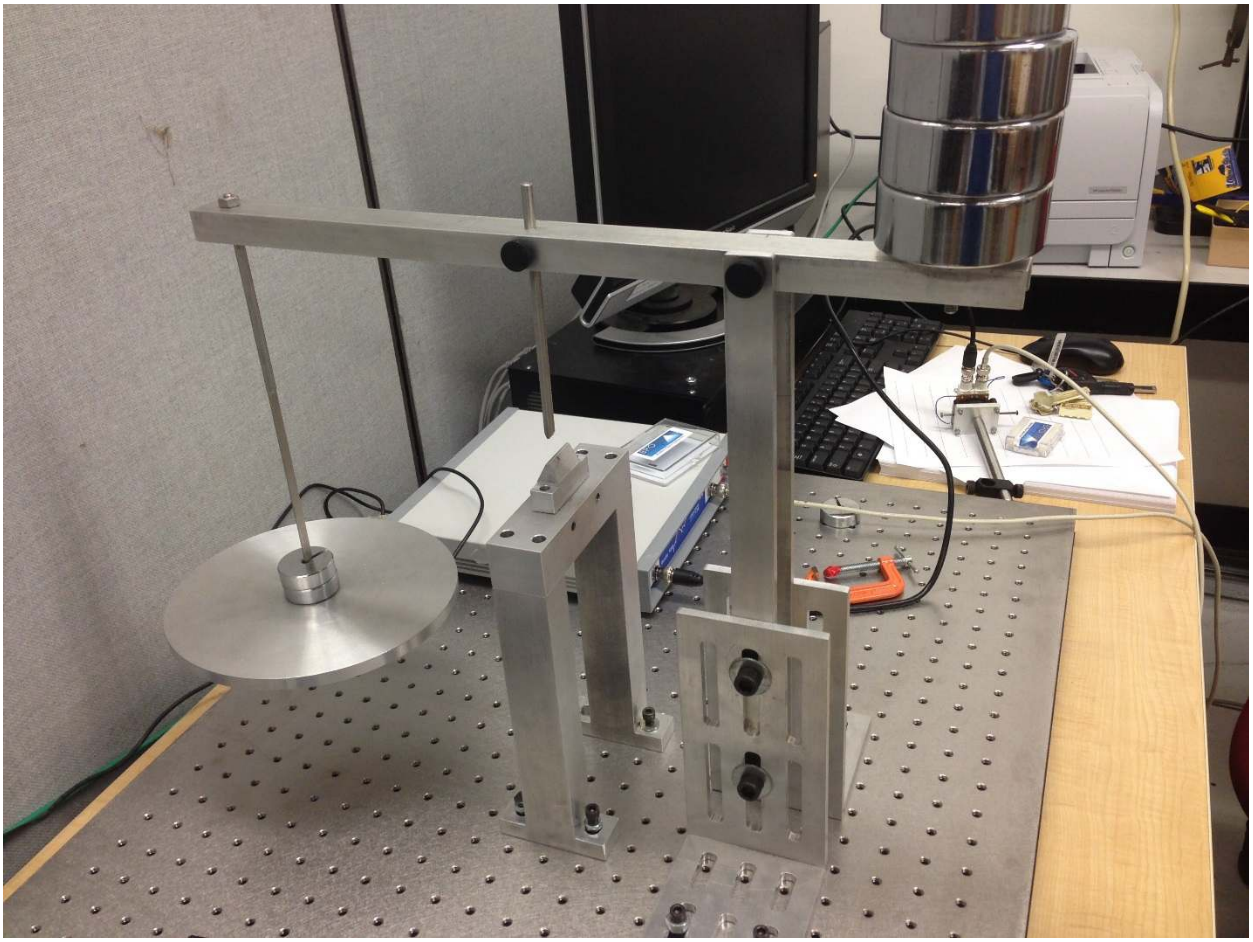


Fig 2.8 Balance

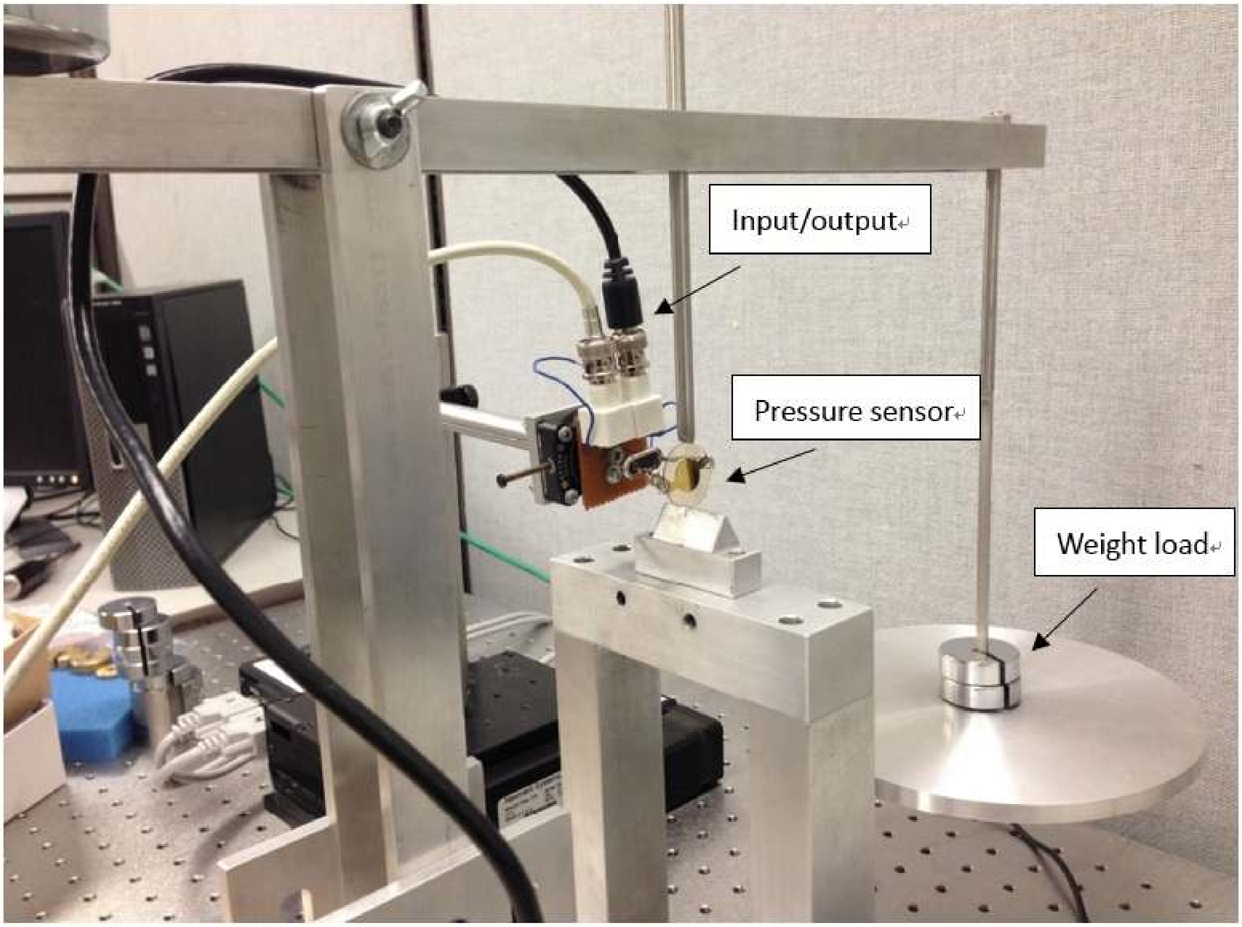


Fig 2.9 Experiment of the piezoelectric effect

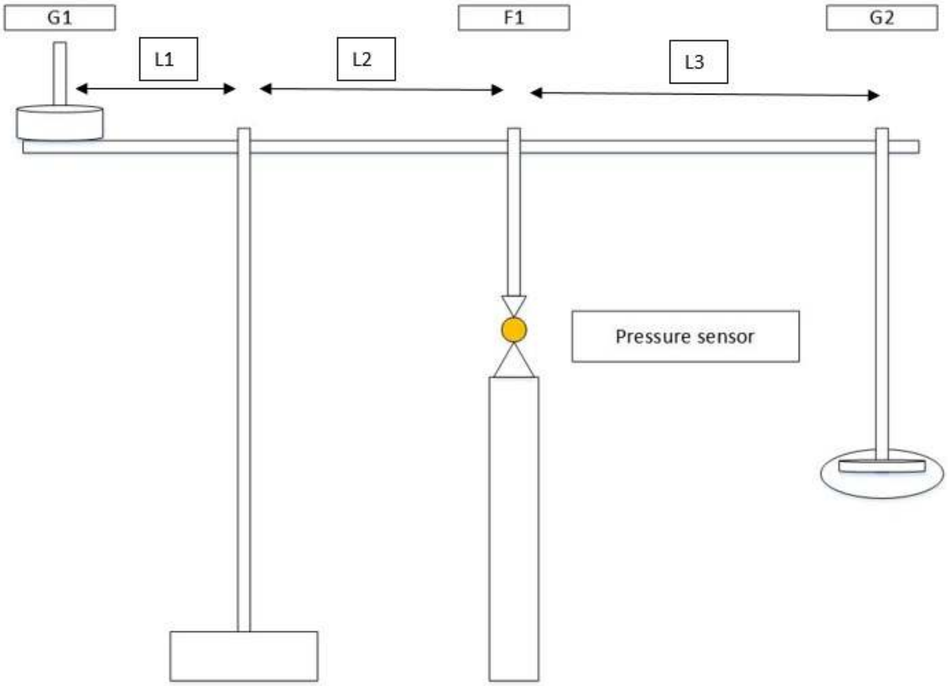


Fig 2.10 Calculation of pressure

According to the moment equilibrium, it is easy to get the equation that

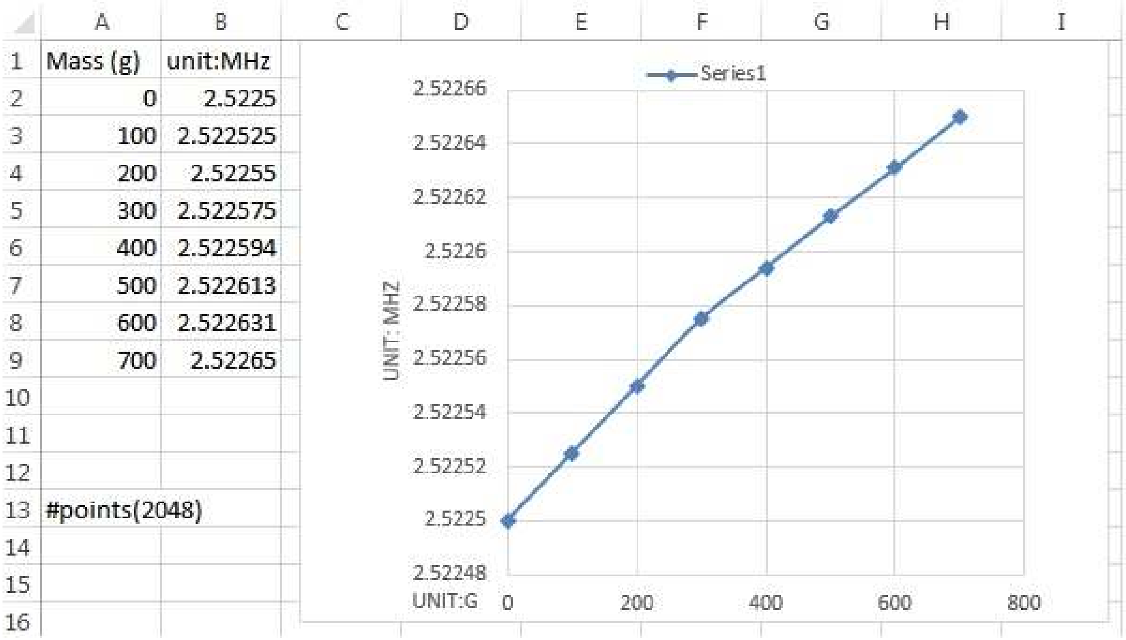
$$G1 * L1 + F1 * L2 = (L2 + L3) * G2$$

Table 2 shows all the value of the variables, F1 can be calculate from the equation above. When 0.7kg weight put on the plate, the pressure is 17.66N.

From Fig 2.11, it is easy to see that as the weight is increased, the resonance frequency gets higher. It can be determined by the curve slope from the figure, that the sensitivity of the sensor is 8.49 Hz/N.

Table 2.1 Value of all the component from the balance

Element Name	Value
G1(N)	39.2
G2(N)	18.248
L1(M)	0.095
L2(M)	0.127
L3(M)	0.2



Mass (g)	unit:MHz
0	2.5225
100	2.522525
200	2.52255
300	2.522575
400	2.522594
500	2.522613
600	2.522631
700	2.52265

#points(2048)

Fig 2.11 Mass vs frequency

CHAPTER 3

PRINCIPLE OF PHASE-LOCKED LOOP

3.1 Introduction

A Phase-Locked Loop (PLL) is a control system that controls the oscillator frequency phase related to the input signal. Basically, PLL consists of three parts: a phase detector (PD), a low-pass filter (LPF) and a voltage controlled oscillator (VCO). Phase detector produces voltage error signal proportional to the phase error. Then the loop filter makes the signal smooth. Finally, the output of the low pass filter is the control voltage of the VCO which produces the output waveform.

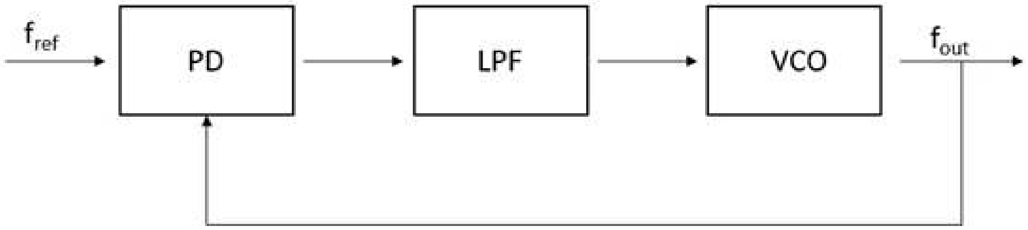


Fig 3.1 Block diagram of a phase-locked loop

3.2 Phase Detector

A phase detector is a circuit whose average output, V_{out}, is linearly proportional to the phase difference, $\Delta\Phi$, between its two inputs. In the ideal case, the relationship between V_{out} and $\Delta\Phi$ is linear, crossing the origin for $\Delta\Phi = 0$. Called the "gain "of the phase detector, the slope of the line, K_{PD}, is expressed in V/rad [10]. Generally speaking, the phase detector is simply an XOR logic gate, with logic low output when both the two inputs are either low or high, and otherwise the logic output will be high.

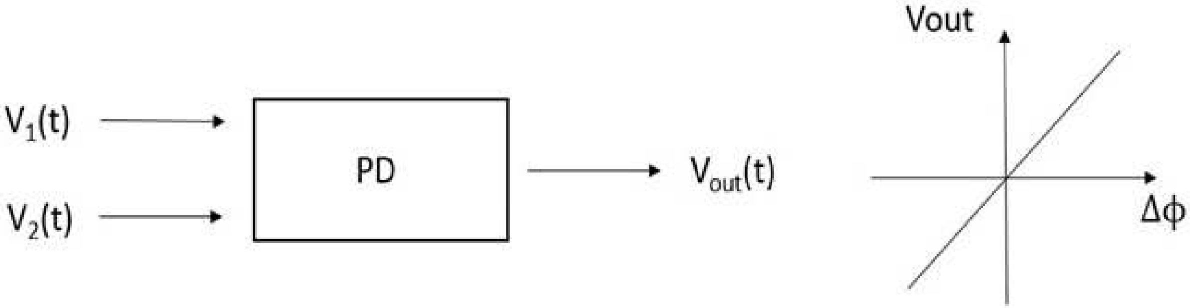


Fig 3.2 Definition of phase detector

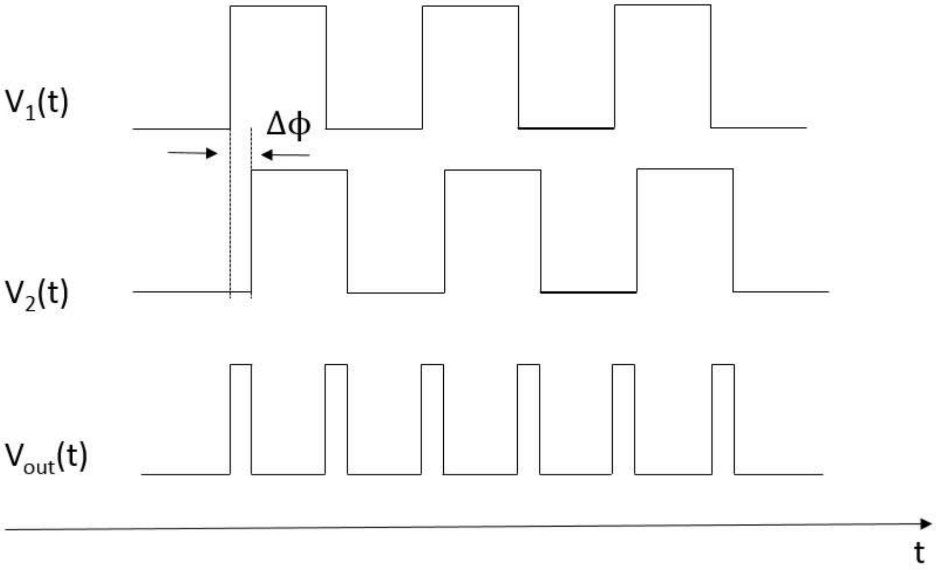


Fig 3.3 Waveform of the phase detector [10]

3.3 Loop Pass Filter (LPF)

The output of the Phase detector produces repetitive pulses at its output signal. The function of the loop pass filter is to transform the output of the phase detector to the signal with less AC component.

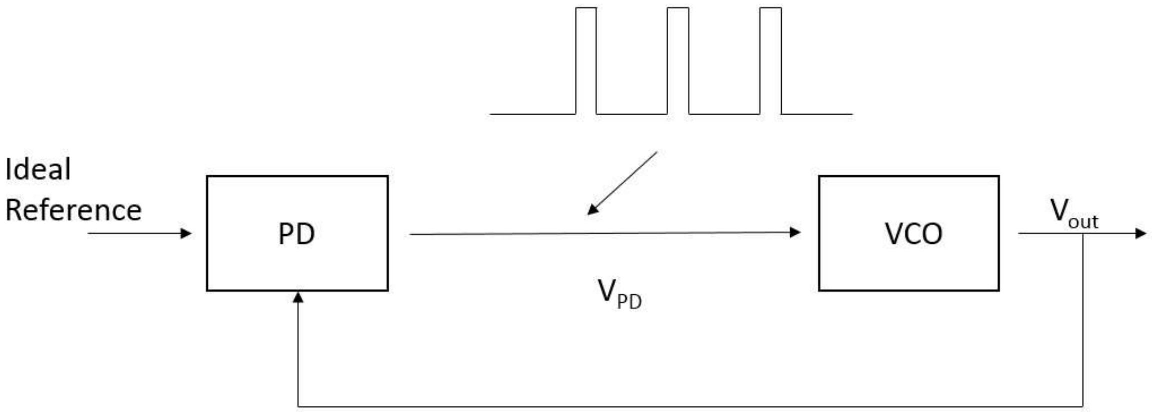


Fig 3.4 Waveform of PLL without LPF

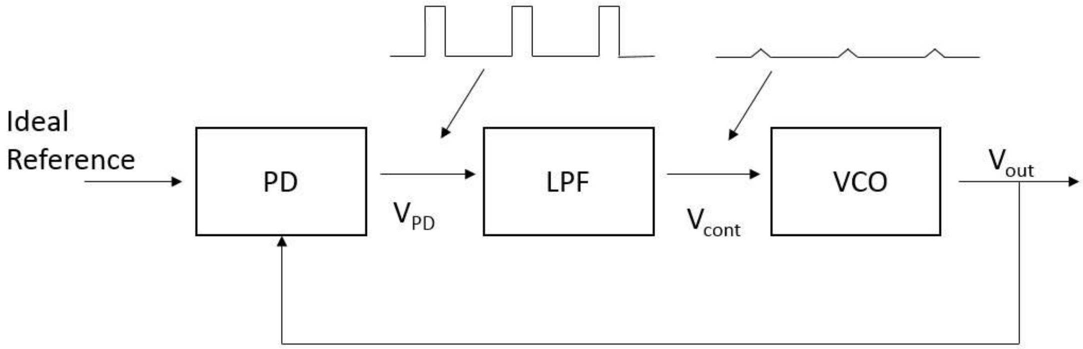


Fig 3.5 Waveform of PLL with LPF

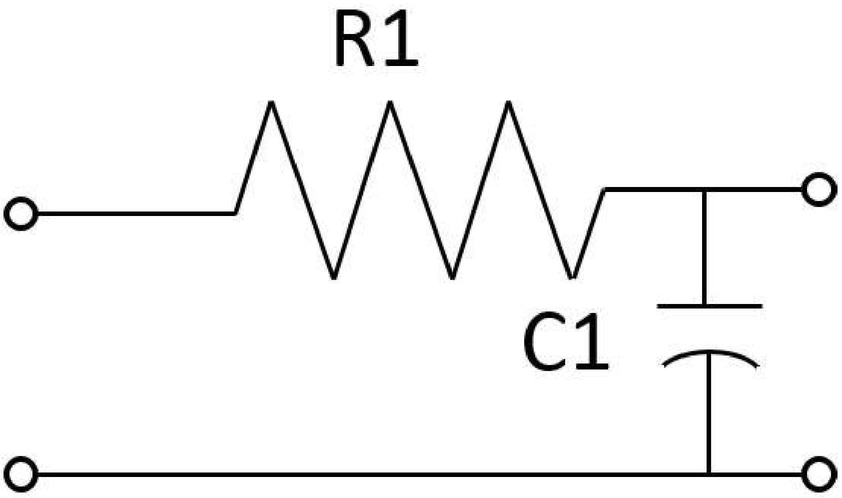


Fig 3.6 RC low pass filter

Normally, we would use a passive loop filter as a loop pass filter. The advantage of the passive loop filter is better linearity, relatively low noise and unlimited frequency range. RC low pass filter is a common type of loop pass filter.

The transfer function of the RC low pass filter is:

$$F(s) = \frac{R_1}{R_1 + \frac{1}{sC_1}} = \frac{1}{1 + s\tau 1}, \tau 1 = R_1 C_1$$

In some cases, active filter is used. The active filter has the advantage of getting poles at the origin and reducing the passive element sizes using trans resistance.

3.4 Voltage Controlled Oscillator

Fig 3.7 Voltage-controlled oscillator

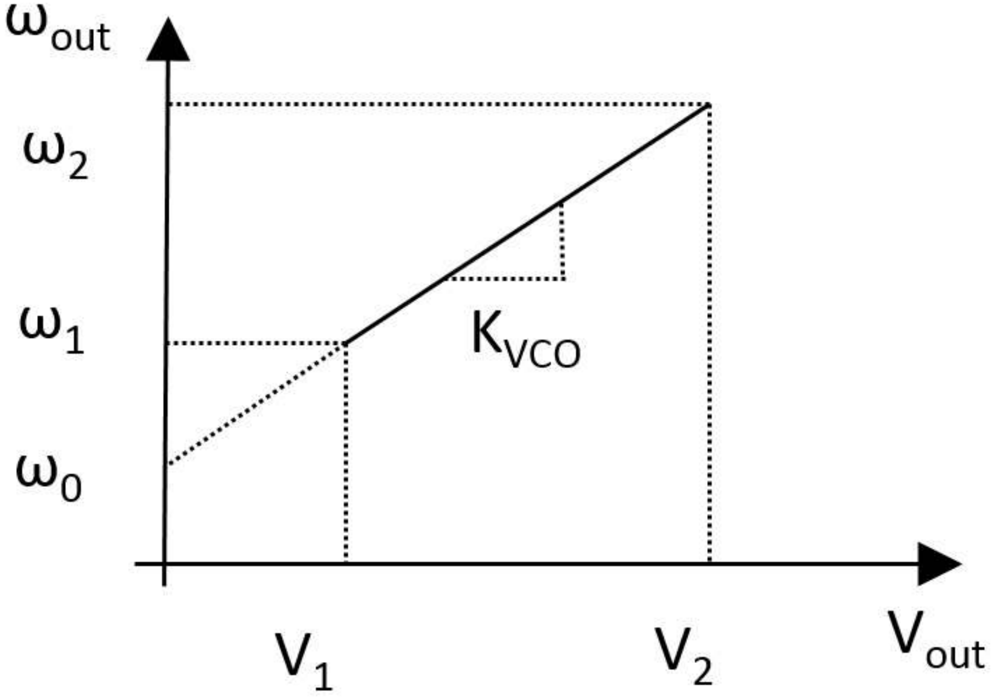


Fig 3.8 VCO characteristic

The input of the VCO is a voltage quantity and the VCO output is a phase quantity. K_{VCO} is the sensitivity of the VCO, and the unit of K_{VCO} is rad/Hz/V. The output of the frequency is the tuning range. K_{VCO} does not change across the range between ω1 and ω2 .The control voltage goes from V_1 to V_2.The formula of the VCO is:

$$\omega_{out} = K_{VCO}V_{cont} + \omega_0$$

3.5 Simulation of the PLL

The Advanced Design System (ADS) is used to run the simulation process. Fig 3.9 shows the whole PLL system. A sine wave voltage source is used as the input of the PLL. The voltage source supports a sine wave signal with 2.342 MHz and 1.84 V of the amplitude as the piezoelectric crystal output.

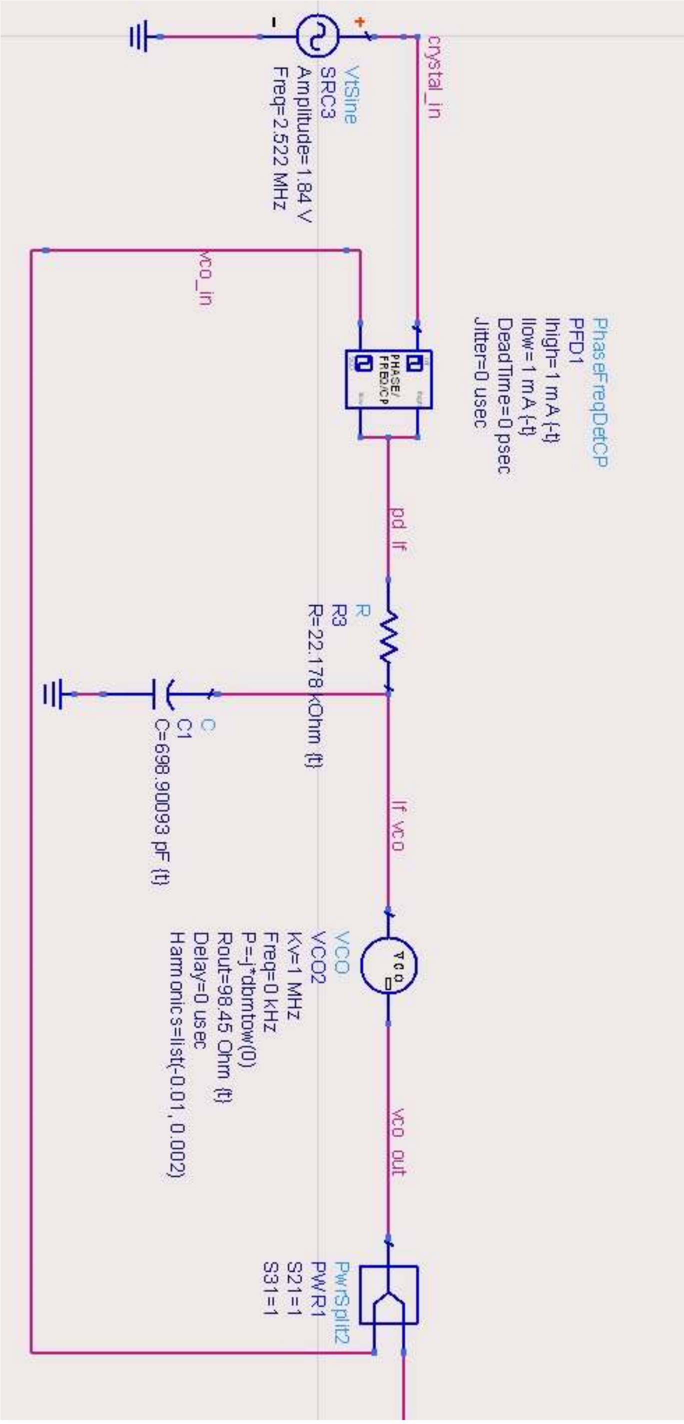


Fig 3.9 PLL simulation

Fig 3.10 illustrates the input of the VCO. After 58.4 microseconds the input of the VCO stays at 2.341. From then the output of the VCO is finally levelling out at around 2.342 MHz; this is called a locked condition. The VCO in the simulation shows that the Kv is the sensitivity of the VCO set at 1MHz/V. So the input of the VCO equals 2.343 V means the output of the VCO equals 2.343 V * 1 MHz/V = 2.343 MHz.

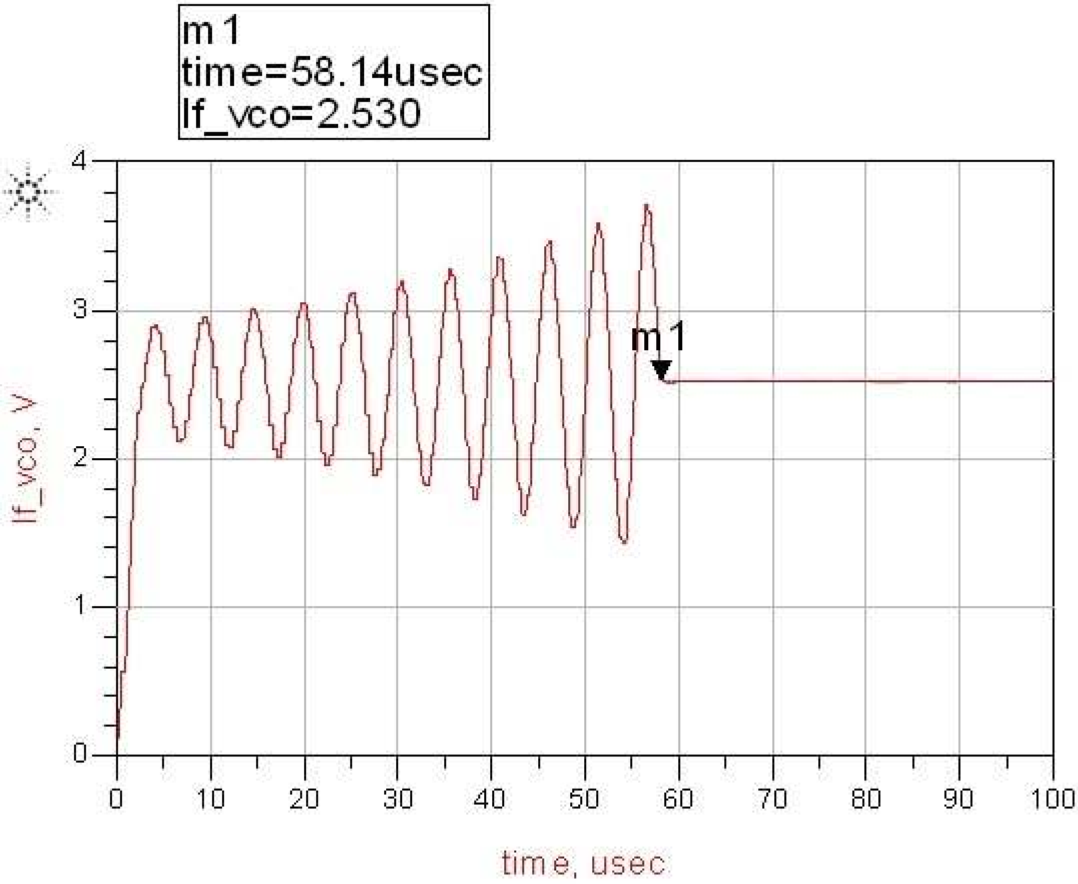


Fig 3.10 Input of the VCO

From the Fig 3.9, it is shown that the output of the VCO supports a feedback to the phase detector. If the output of the VCO has the same phase diagram with the input signal, it is said that the PLL is in the locked condition. Fig 3.11 compares the input signal with another input from VCO feedback.

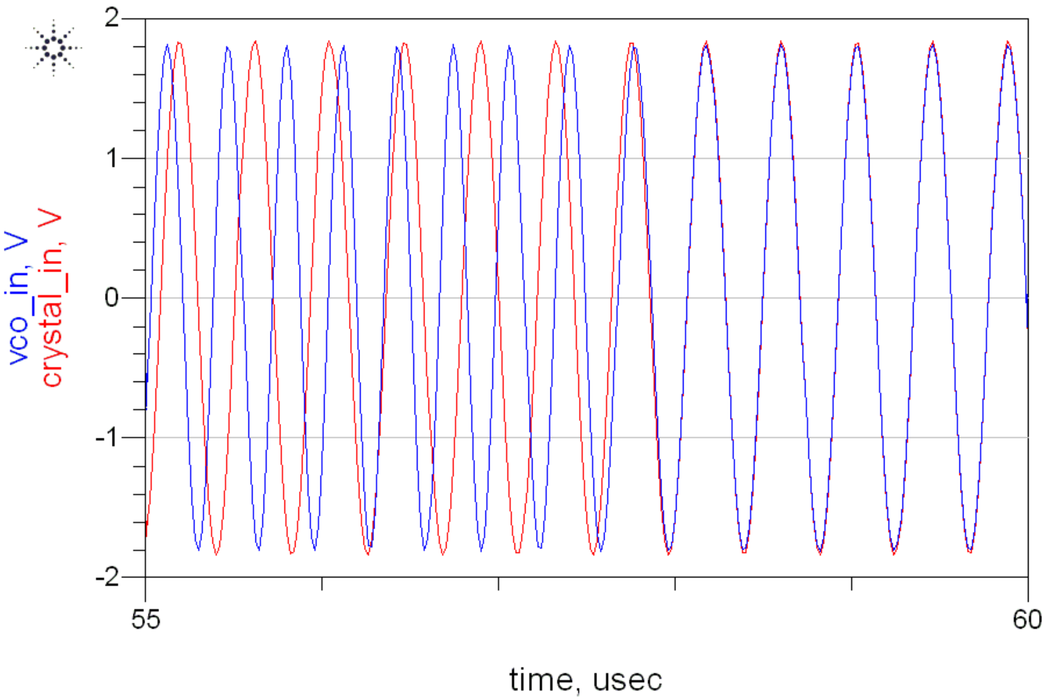


Fig 3.11 Two inputs of the PLL

3.6 Conclusion

From the simulation of the PLL, we know that the function of the PLL in the frequency output pressure transducer is achievable. The changing frequency of the pressure crystal is tracked by the phase-locked loop circuit.

CHAPTER 4

DESIGN OF THE PERIPHERAL CIRCUIT

4.1 Crystal Oscillator

4.1.1 Introduction

In order to activate the piezoelectric crystal, a crystal oscillator is used. According to the piezoelectric effect, the piezoelectric crystal is able to supply frequency if a voltage is applied. A crystal oscillator is the circuit which uses feedback to activate the piezoelectric crystal to create an electrical signal with a very precise frequency.

4.1.2 Pierce Oscillator

A Pierce oscillator is a type of an electronic oscillator particularly well-suited for the use in piezoelectric crystal oscillator circuits. The circuit was named by the inventor George W Pierce. Pierce oscillator derives from Colpitts oscillator. Because of the simple structure and the way it works effectively and stably, it is used widely in the crystal oscillator. A simple Pierce oscillator only needs a single CMOS inverter, resistors capacitors and a piezoelectric crystal. Fig 4.1 shows the topology of Pierce oscillator.

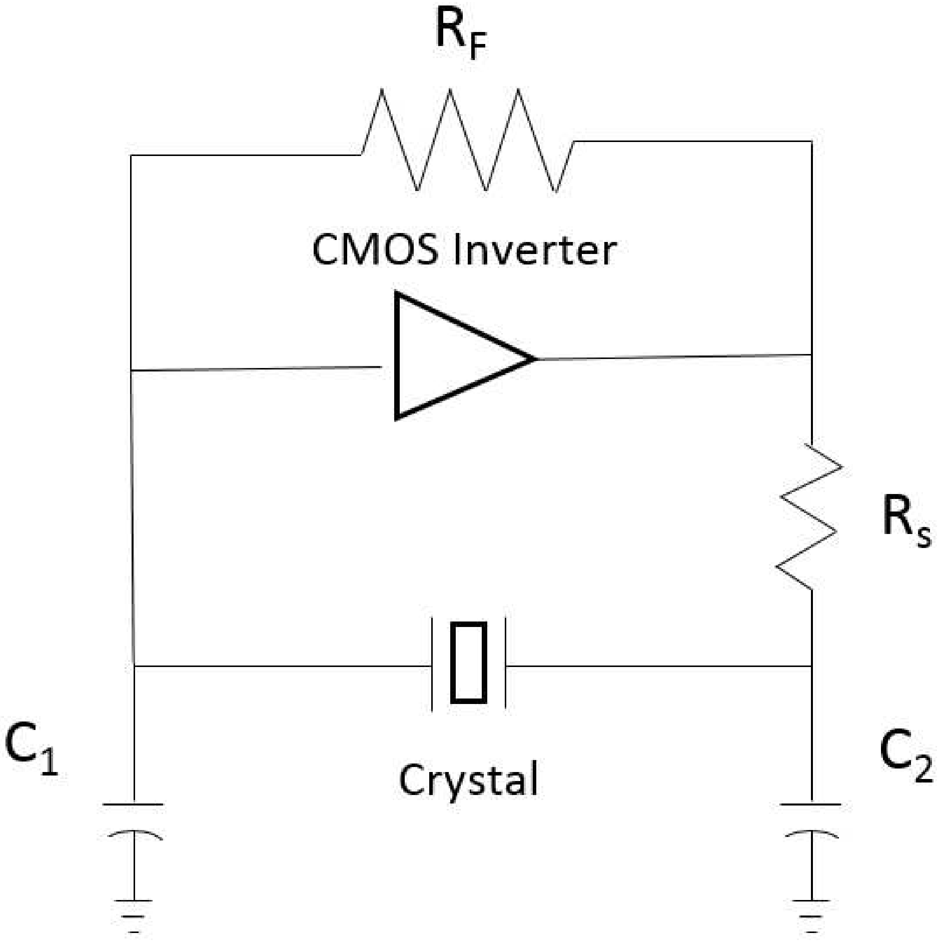


Fig 4.1 Pierce oscillator

4.1.3 Operation of Pierce Oscillator

4.1.3.1 Biasing Resistor

R_F in the Fig 4.1 is named a Biasing resistor. It acts as a feedback resistor, biasing the inverter in the linear region of the operation. Thus the inverter becomes a high gain inverting amplifier.

4.1.3.2 Resonator

The piezoelectric crystal resonator and C1 and C2 forms a pi network band-pass filter. The working frequency is about the resonance frequency of the piezoelectric crystal. The resonator also supplies 180 degree phase shift and the voltage gain. In the resonator, the crystal can be considered a high Q inductor.

4.1.3.3 Isolation Resistor

In the Fig 4.1, R_s is an isolation resistor. R_s connects in series the output of the inverter and the crystal. The function of the R_s is isolating the output with the pi network. The main purpose of the R_s is to suppress the high frequency spurious oscillation to get the pure output signal.

4.2 Mixer

4.2.1 Introduction of Mixer

To get the difference with the pressure sensor frequency and the reference frequency, a mixer is a good choice for this design. The function of the mixer is to translate frequency by multiplying the two input waveforms. In the receive mode, down-conversion mixer receives the signal from the “RF port” and another input signal from local oscillator called “LO port”. The output of the down-conversion mixer comes from its “IF port”. In the transmit modes, upconversion mixer’s input is through the “RF port” and the output is from the “IF port”. The input is also affected by the “LO port”. Fig 4.2[10] shows the diagram of the down-conversion mixer and the up-conversion mixer is shown in Fig 4.3[10].

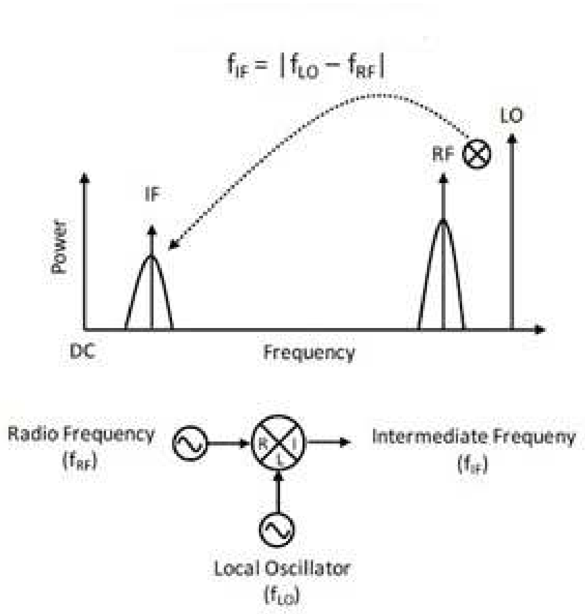


Fig 4.2 Down-conversion mixer [10]

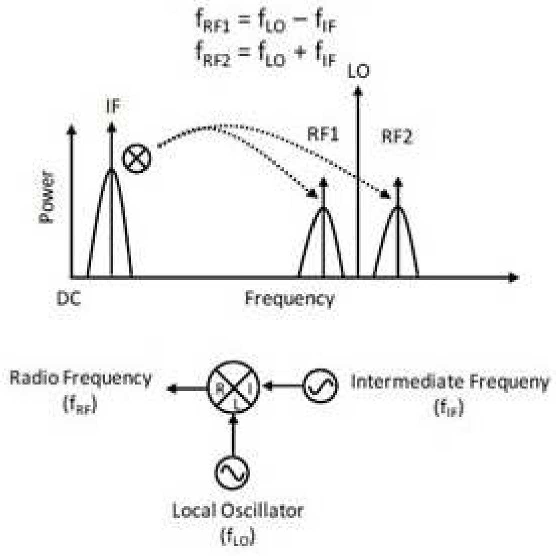


Fig 4.3 Up-conversion mixer [10]

4.3 Application in Frequency Output Pressure Transducer

In this design, the input of the mixer is the output of the PLL and a reference crystal connects with the LO port as the local oscillator. The down-conversion mixer output equals to the frequency difference between the pressure sensor and a reference sensor. As shown in Fig 4.4, the crystal_in is the input of the crystal oscillator circuit which is the resonance frequency of the pressure sensor. LO port connects with a voltage source as the signal from reference sensor. Output of the mixer in Fig 4.4 is called rf_fc which equals the difference between reference sensor and pressure sensor. Fig 4.5 is the simulation of the mixer with RF and LO signal.

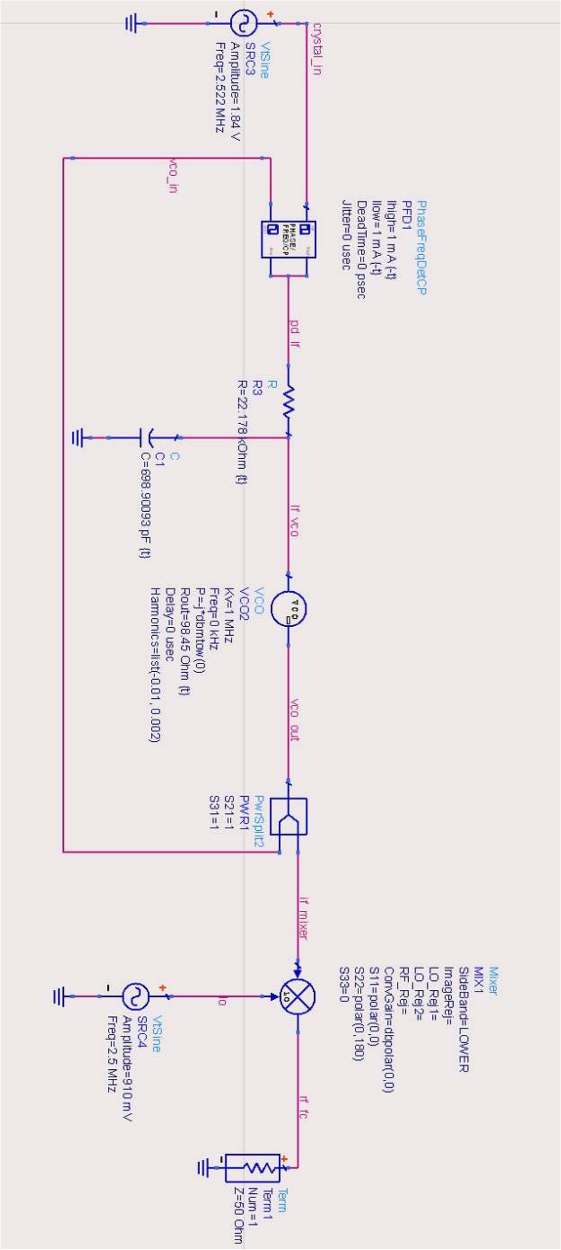


Fig 4.4 Simulation circuit of the transducer

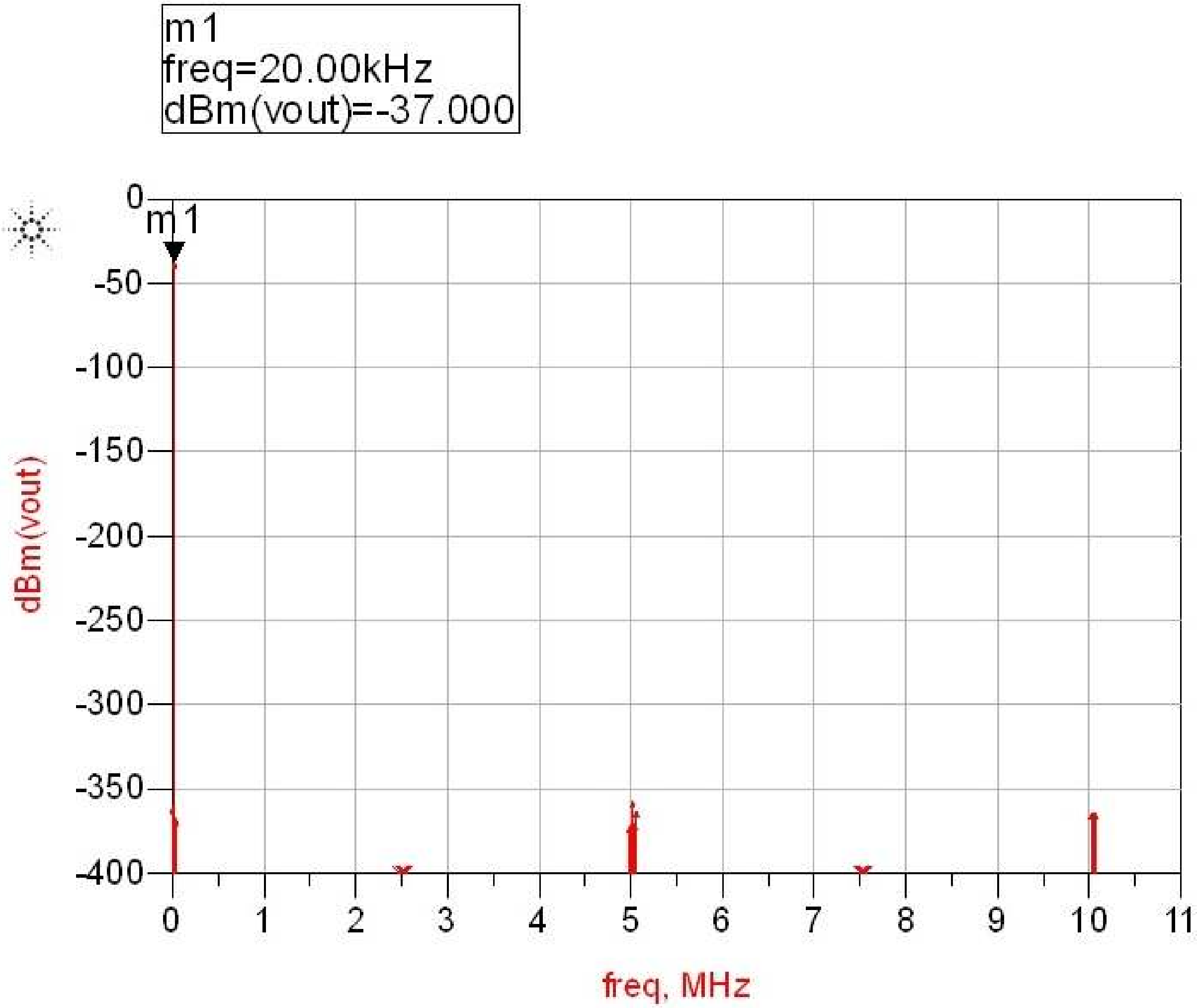


Figure 4.5 Simulation result of the mixer

CHAPTER 5

IMPLEMENTATION AND MEASUREMENT

5.1 Crystal Oscillator Circuit

HCF4069 is one of the most common inverter circuit chips and it is suitable for a crystal oscillator. By using the pierce oscillator design, one inverter is used in the circuit as an amplifier to supply power for the closed system. There is another inverter used as the amplifier for the pierce oscillator to amplify the oscillator output voltage to a level sufficient for follow-up use.

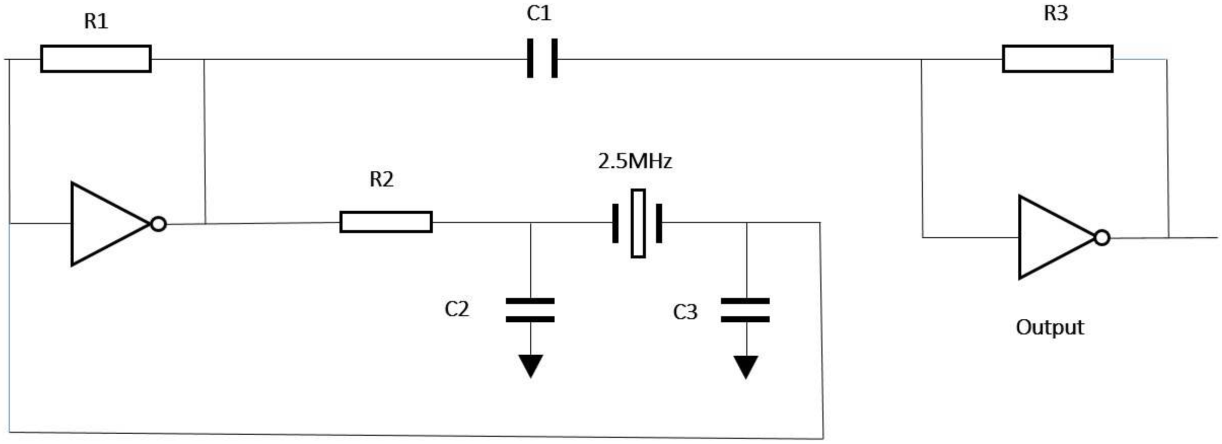


Fig 5.1 Crystal oscillator

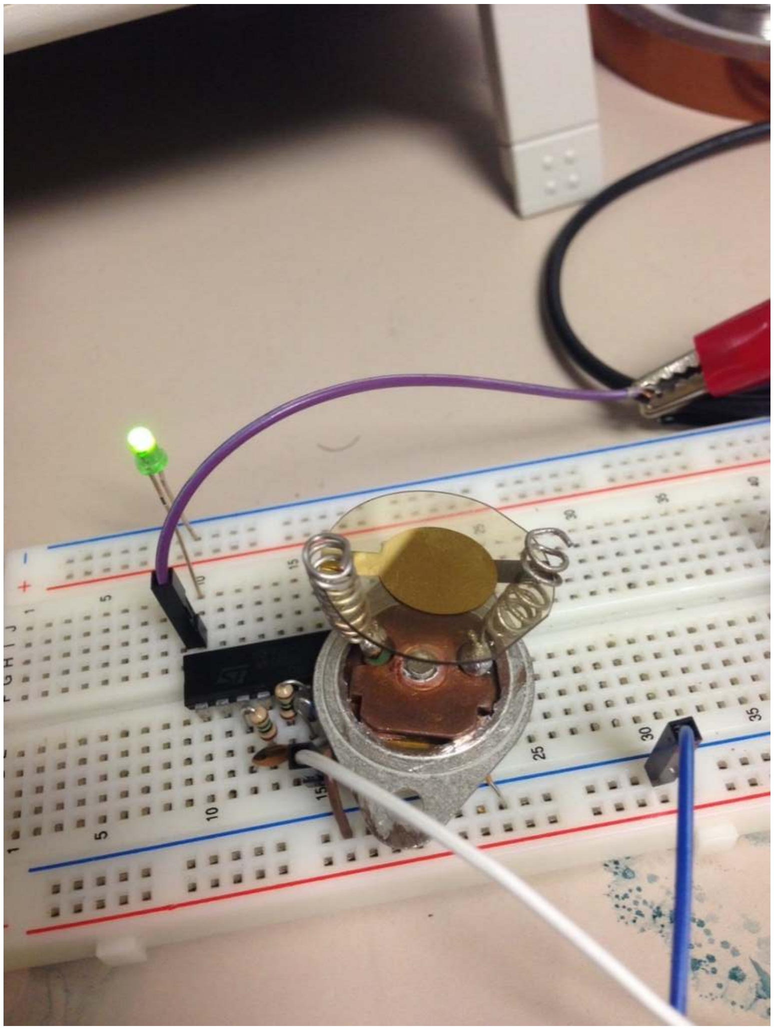


Fig 5.2 Crystal oscillator circuit

From the Fig 5.2, the crystal oscillator connects with the crystal successfully. The 5 volts supply voltage plugs into the chip and the output of the circuit connects to oscilloscope. The output of the circuit is shown on the oscilloscope plotted in Fig 5.3. The measurement results of all the components are listed in Table 5.1

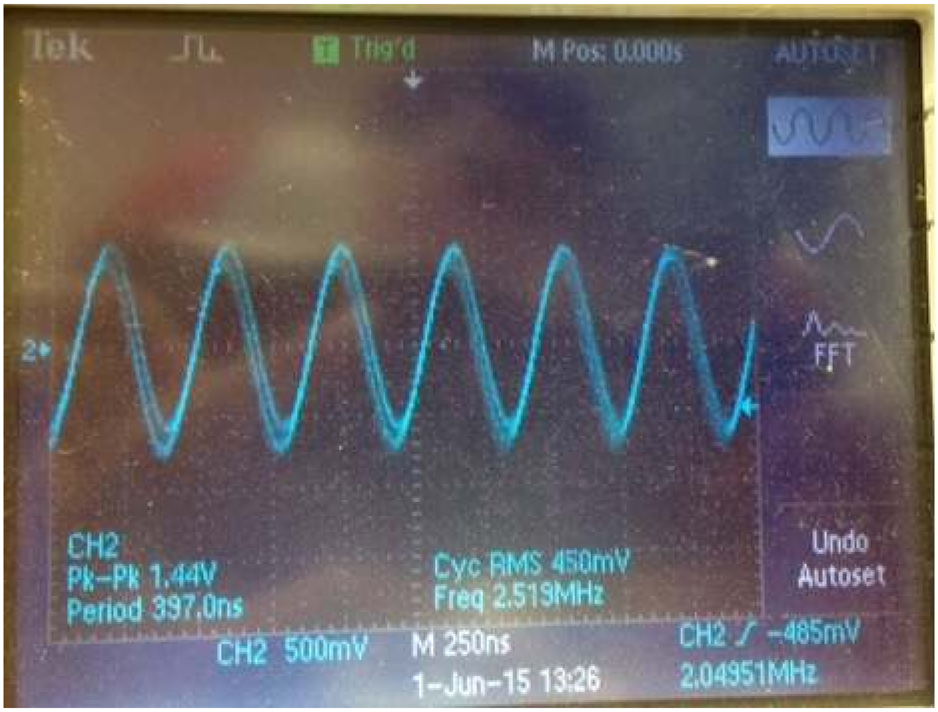


Fig 5.3 Output signal of the crystal oscillator circuit

TABLE 5.1 VALUES OF THE LUMPED ELEMENTS IN CRYSTAL OSCILLATOR CIRCUIT

Element name	Value
R1(Ω)	1M
R2(Ω)	2.2k
R3(Ω)	1M
C1(pF)	22
C2(pF)	100
C3(pF)	22

5.2 Phase-Locked Loop

The operation frequency of the crystal oscillator is nearly 2.5 MHz and in this level there are few components that can be selected. 4046 is a classic type of the PLL and HEF4046 is an excellent model which is manufactured by NXP semiconductors. Fig 5.4 [26] shows the functional diagram of the chip.

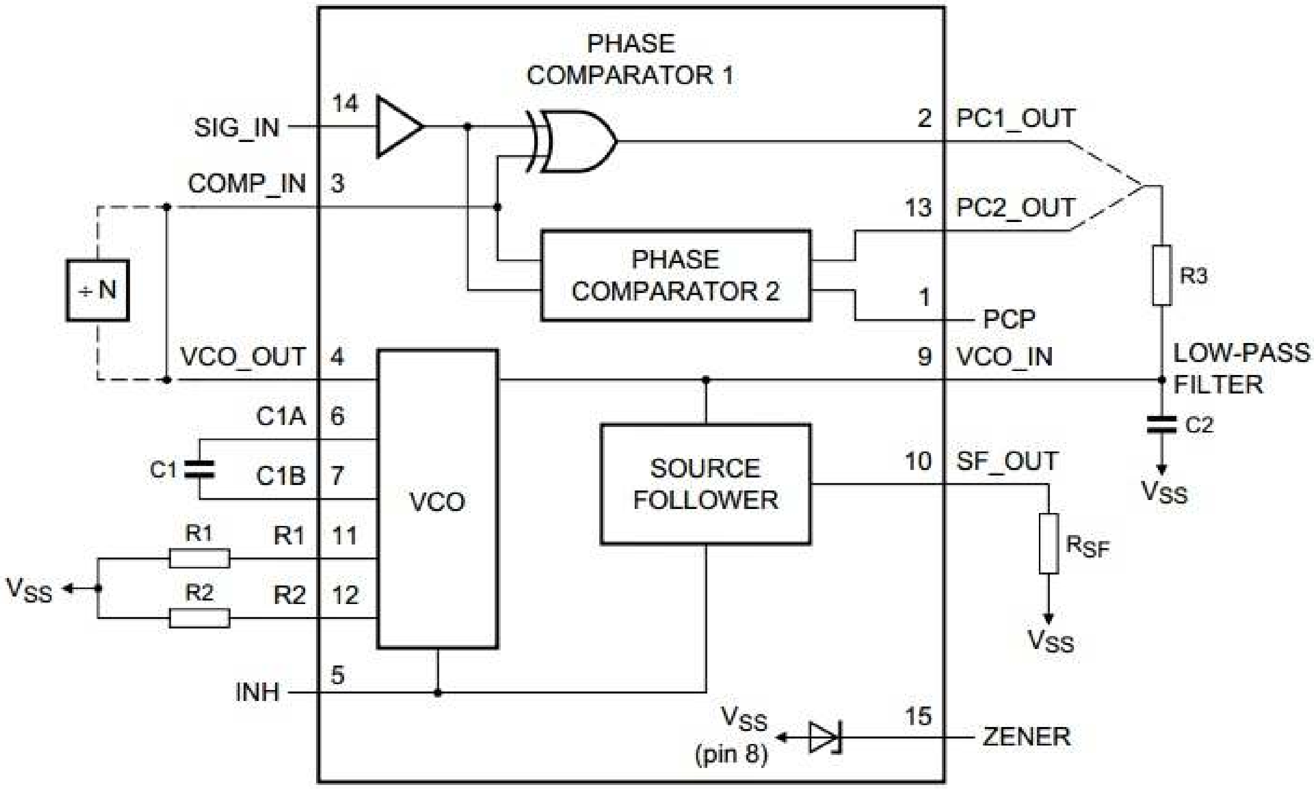
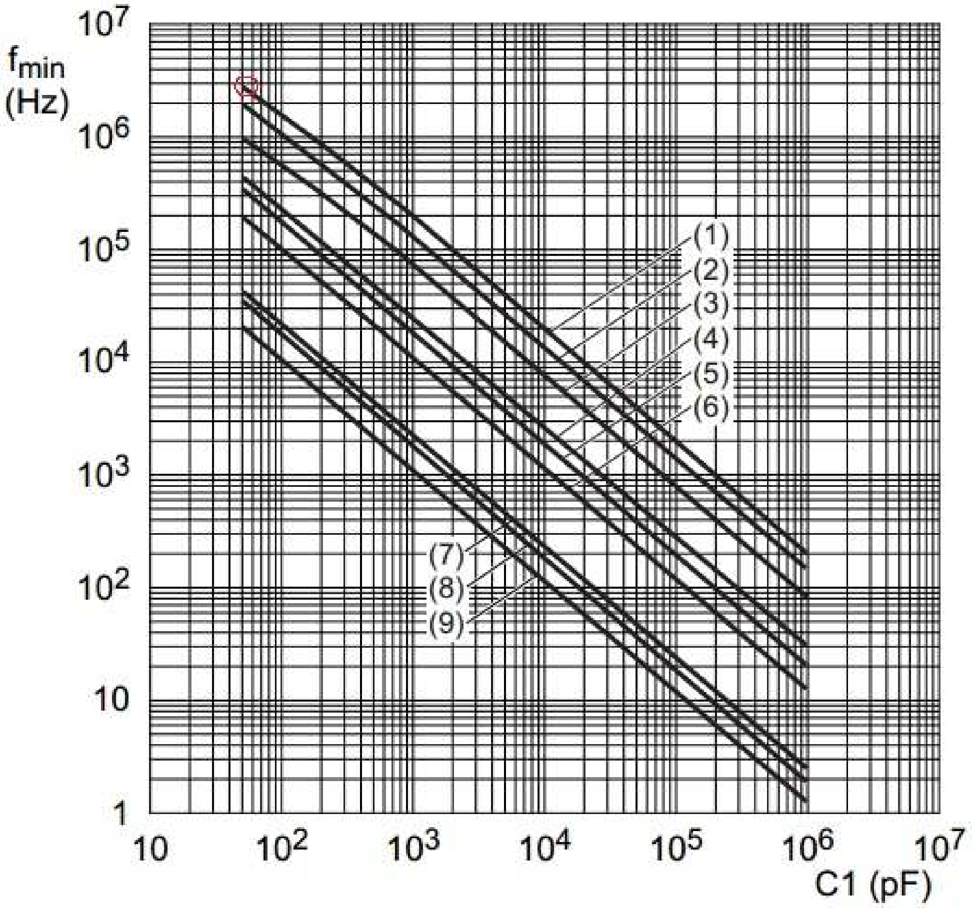


Fig 5.4 Block diagram of PLL

The target frequency range is from 2.33 MHz to 2.4 MHz. With the figure from the HEF4046B datasheet, it is easy to get all the component value. From Fig 5.5[26], it is possible to observe that if the output frequency is 2.33 MHz, the value of C1 is 50 pF and V_{DD} is 15 V.



T_{amb} = 25 °C; VCO_IN at V_{SS}; INH_IN at V_{SS}; R1 = ∞.

Lines (1), (4), and (7): V_{DD} = 15 V;

Lines (2), (5), and (8): V_{DD} = 10 V;

Lines (3), (6), and (9): V_{DD} = 5 V;

Lines (1), (2), and (3): R2 = 10 kΩ;

Lines (4), (5), and (6): R2 = 100 kΩ;

Lines (7), (8), and (9): R2 = 1 MΩ.

Fig 5.5 Relationship between f_{min} and C1

As indicated in Fig 5.6[26], use f_{max}/f_{min} to determine R_2/R_1 to obtain R_1.

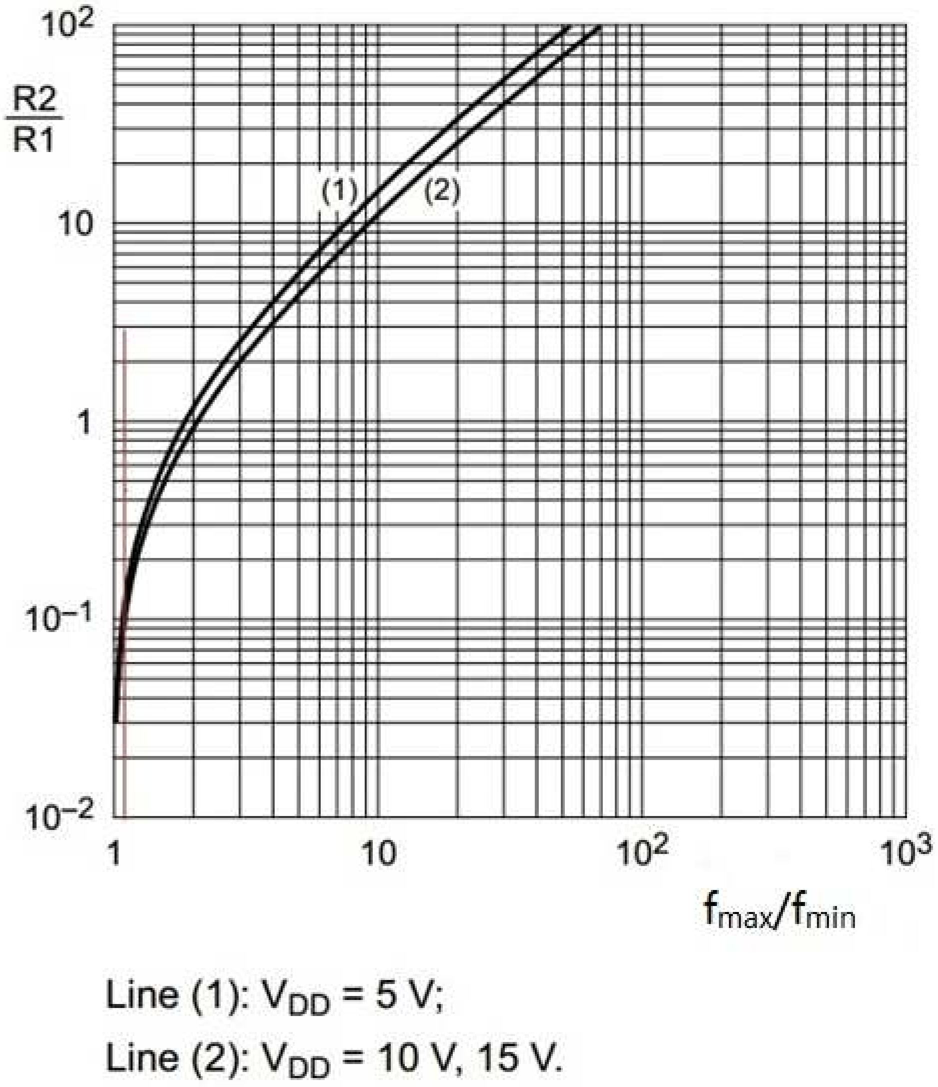


Fig 5.6 Relationship between R2/R1 and f_{max}/f_{min}

As presented in Chapter 3, an RC filter is used as the low pass filter in the PLL.

The value of resistor and capacitor can be calculated from the equation:

$$F_{cut-off} = \frac{1}{2\pi RC}$$

In general, the cut-off frequency is smaller than half of the output frequency. In this design, the cut-off frequency equals to 0.233 MHz. So it is easy to get the value of the RC filter.

According to the datasheet of HEF4046 and the specification of the design, all the component values are listed in Table 5.2.

TABLE 5.2 Values Of The Lumped Elements Of Phase-Locked Loop Circuits

Element name	Value
$R1(\Omega)$	66.67k
$R2(\Omega)$	10k
$R3(\Omega)$	1k
$C1$(pF)	50
$C2$(pF)	680

Fig 5.7 shows the circuit in which crystal oscillator is connected to the PLL and Fig 5.8 shows the output of the PLL. The waveform of the oscilloscope indicates that the circuit is working properly.

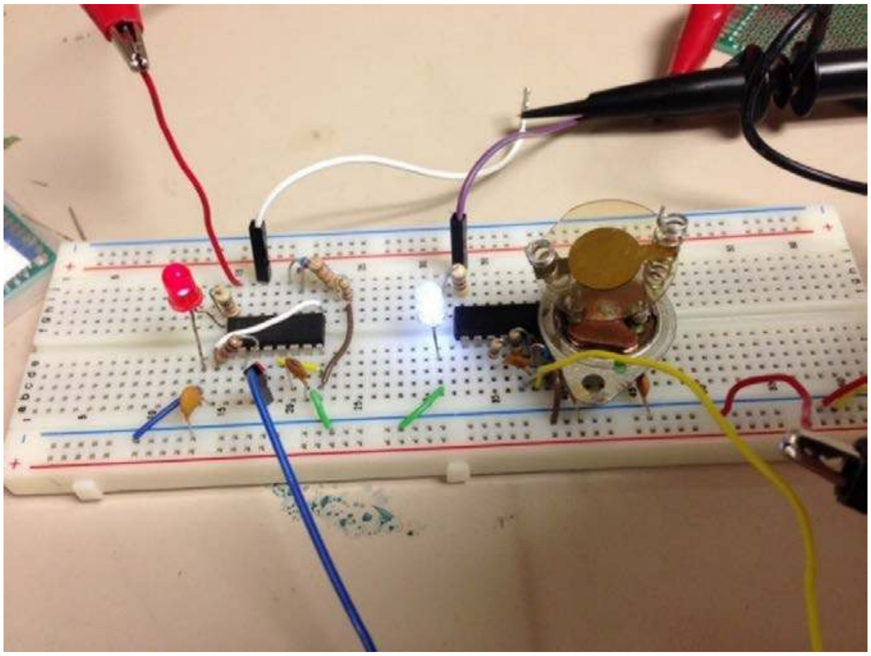


Fig 5.7 Circuit of the PLL and crystal oscillator

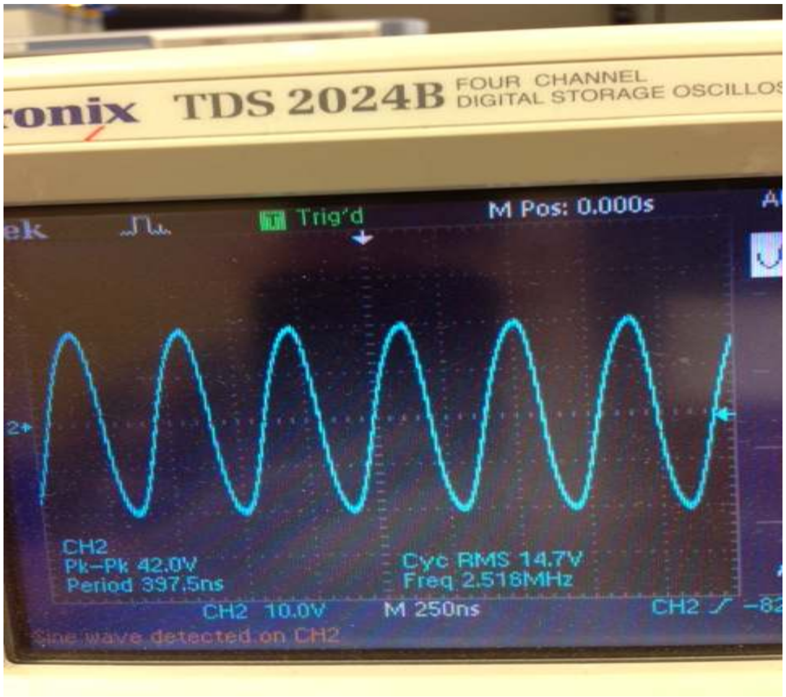


Fig 5.8 Output signal of the PLL

The PCB circuit board is used to replace the simple breadboard to improve the performance of the circuit. Fig 5.9 and Fig 5.10 show the picture of the PCB board. The chemical etching method is used to make PCB board.

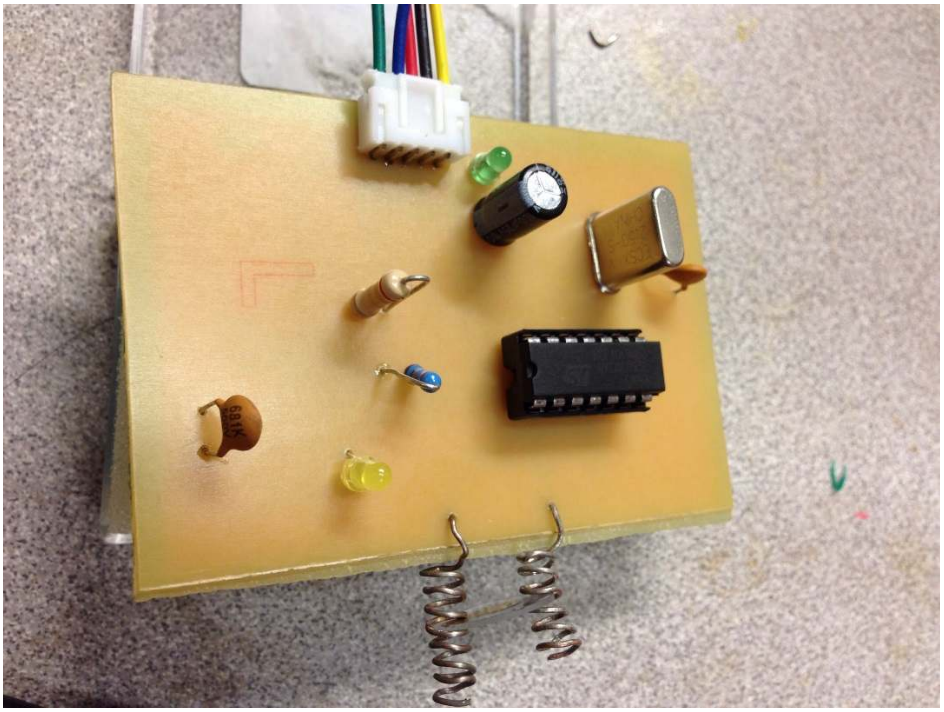


Fig 5.9 Front of the PCB board

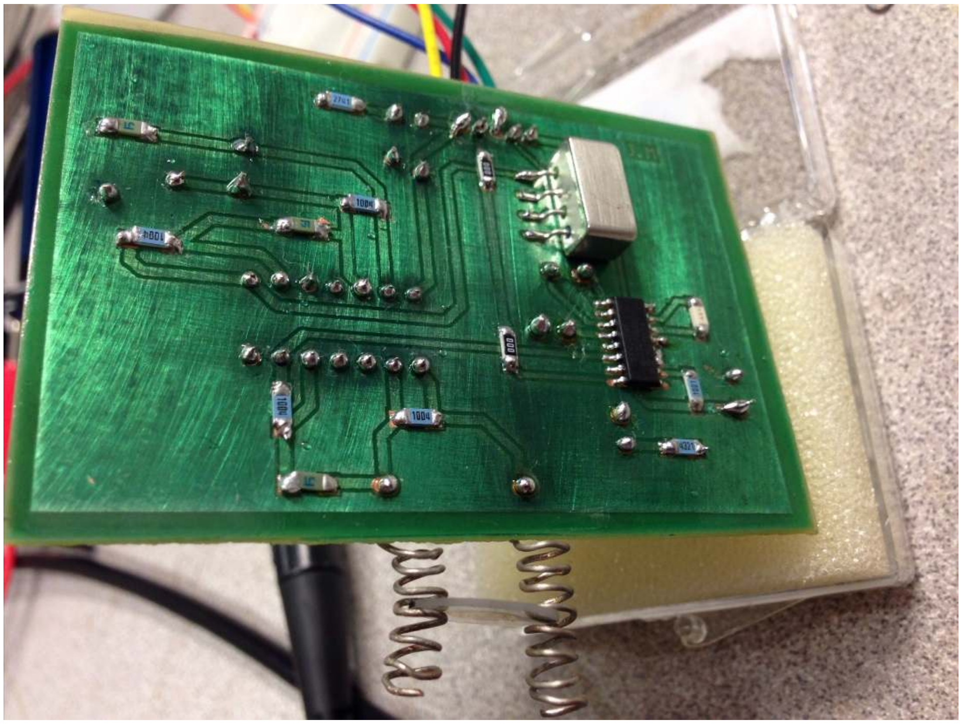


Fig 5.10 Back of the PCB board

Frequency counter is an important part of a portable transducer. It shows the frequency of the output signal from the transducer as an oscilloscope. The frequencies of the reference crystal and pressure sensor are shown in the Fig 5.11 and Fig 5.12, and Fig 5.13 indicates the output of the system.

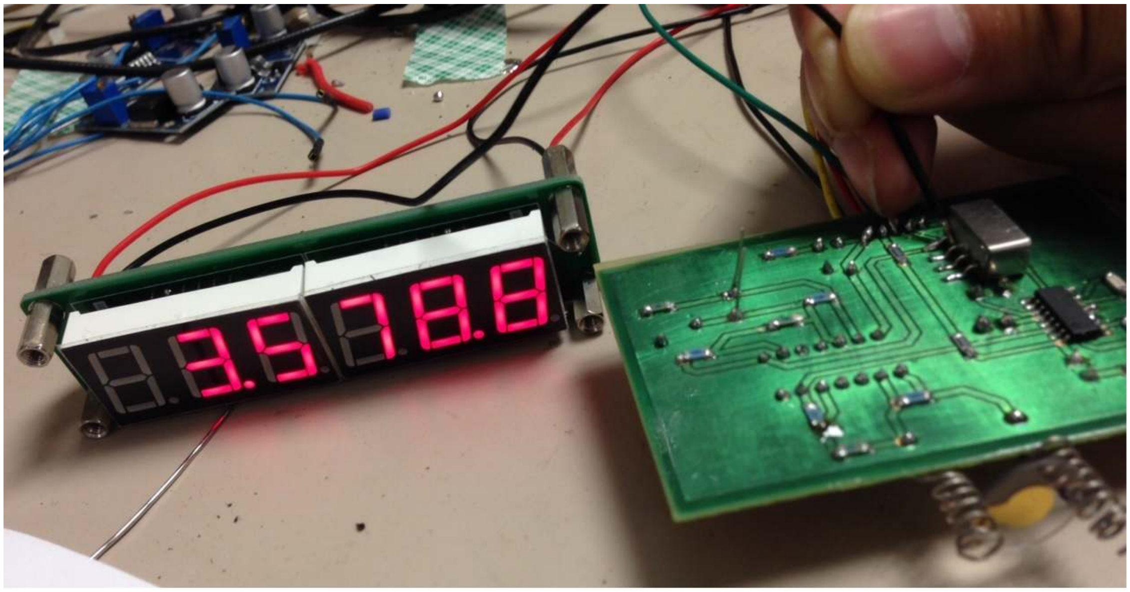


Fig 5.11 Frequency of reference crystal

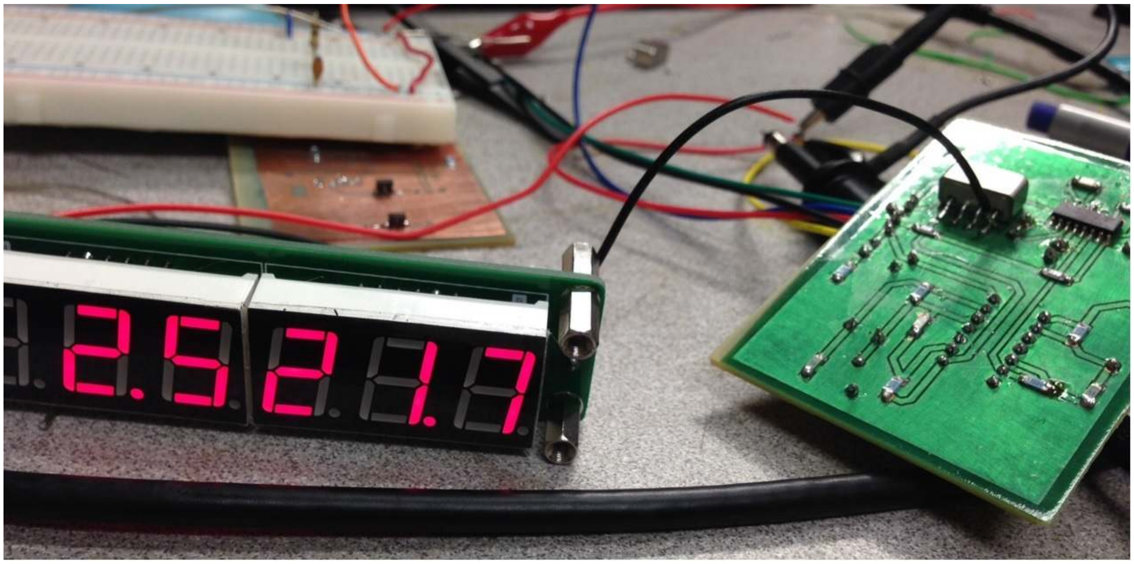


Fig 5.12 Frequency of pressure sensor

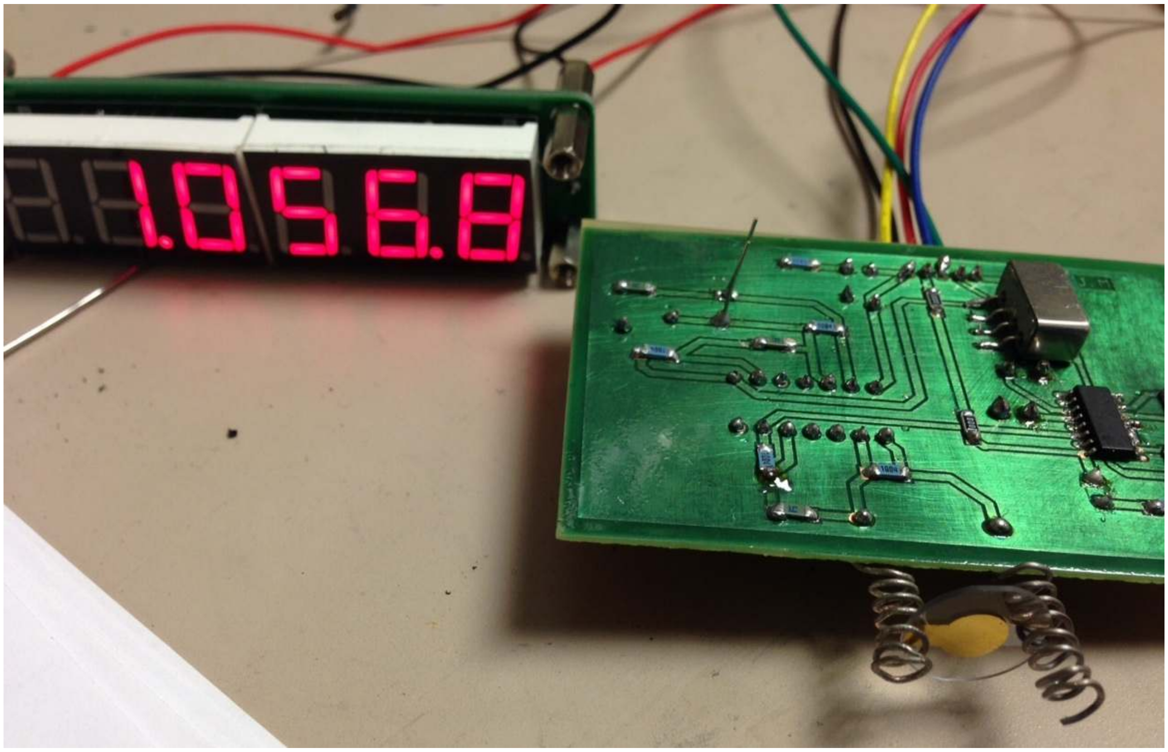


Fig 5.13 Output of the circuit

The output of the circuit is the frequency difference of the reference and the pressure sensor. Thus, the pressure applied on the sensor is reflected through the frequency change. The higher pressure applied, the higher frequency output circuit is.

CHAPTER 6

CONCLUSION AND FUTURE WORK

This thesis presents the complete process of the design of the frequency output pressure transducer. The principles of a phase-locked loop, a crystal oscillator, and a mixer are introduced. The fundamental feature of piezoelectric effect is also mentioned. First, HCF4069 is used to activate the pressure sensor and the reference crystal to provide two kinds of input frequency for the mixer. Then, the frequency signal of the pressure sensor is connected to the PLL chip and the output of the PLL is connected to the mixer as the RF signal. A mixer with a low pass filter is used as the signal processing system in the design and the output of the transducer equals the frequency difference of the pressure sensor and the reference crystal. The value of the output frequency reflects the pressure applied on the sensor. The whole working process of the transducer is clearly presented in the thesis.

Due to the limit of the size of the pressure sensor, it is difficult to measure its frequency change. From the measurement result of the bode analyzer (see Fig 2.11), it is shown that the frequency change of the pressure sensor is about 120 Hz. The frequency difference of the pressure becomes more obvious with the higher pressure applied on the pressure sensor. Thus, if a sensor with a larger size and structure that can afford higher pressure is used in the future, the performance of the circuit will be better.

In the future, a temperature crystal also can be used as another sensor, so the change of the temperature also can be detected from the frequency change. Furthermore, the size of the transducer can be reduced. Moreover, in order for it to be a complete transducer, a metal tube is needed. A metal tube can protect the inner circuit from external environment effect, such as electromagnetic interference (EMI), high temperature and high humidity. The transducer with temperature sensor and metal tube will have a compact size and great potential for industry applications.

REFERENCES

[1] George W. Pierce (October 1923) "Piezoelectric crystal resonators and crystal oscillators applied to the precision calibration of wavemeters," *Proceedings of the American Academy of Arts and Sciences*, vol. 59, no. 4, pages 81-106.

[2] W. P. Mason (Ed.), *Physical Acoustics*, Academic Press, New York (1964), vol. 1 Part A.2.

[3] W. G. Cady, Dover Publications, *Piezoelectricity*, New York, (1964) and McGraw-Hill Book Co., (1946).3.

[4] E. A. Gerber and A. Ballato (Ed.), *Precision Frequency Control*, Academic Press, New York (1985), vol. 1.4.

[5] O. E. Mattiat, *Ultrasonic Transducer Materials*, Plenum Press, London, New York, (1971).5. [6] G. S. Kino, *Acoustic Waves: Devices, Imaging, and Analog Signal Processing*, Prentice Hall, Englewood Cliffs, NJ, (1987).

[7] Roland E.Best, *Phase-Locked Loop: Design, Simulation, and Applications,Sixth* , McGraw-Hill,2004

[8] Ensaka Junaki, translated by Xicai He, “The phase-locked loop PLL circuit design and application”, Science Press, CHINA, BEIJING (2006)

[9] B. Razavi, *Design of Analog CMOS Integrated Circuits*, 2001: McGraw-Hill

[10] B. Razavi*, RF Microelectronics*, 1997: Prentice-Hall

[11] F.Della Lucia and P.Zambrozi Jr. “Design, fabrication and characterization of SAW pressure sensors for offshore oil and gas exploration” *Sensors and Actuators A: Physical*, Vol.222, pp.322-328, Feb.2015

[12] H.E. Karrer, J.G. Leach, *Quartz resonator pressure transducer*, United States Patent #3,561,832, 1971.

[13] E.P. EerNisse."Quartz resonator frequency shifts arising from electrode stress", *Proceedings of the 29th Annual Symposium on Frequency and Control* (1975), pp. 1–4

[14] A. Ballato, Basic material quartz and related innovations, Piezoelectricity, *Evolution and Future of a TechnologySpringer* (2008), pp. 9–35 (Chapter 1)

[15] E.P. EerNisse, R.B. Wiggins, Resonator temperature transducer, United States Patent #4,592,663, 1986.

[16] R.J. Besson. A dual-mode thickness-shear quartz pressure sensor, *Proceedings of the Ultrasonics Symposium* (December 1991)

[17] R.W. Ward, R.B. Wiggins, Quartz Pressure Transducer Technologies, (May 1997) available at: http://www.quartzdyne.com/pdfs/techqptt.pdf

[18] Eric Vittoz, *Low-Power Crystal and MEMS Oscillators*, 2010: Springer

[19] G.W. Pierce, "Electrical System". US patent 2, 133, 642, filed Feb.25, 1924, issued Oct.18, 1938

[20] Antonio Arnau, *Piezoelectric Transducers and Applications*, Springer, 2008.

[21] V.Ferrair, D.Marioli, and A.Taroni "Oscillator circuit configuration for quartz crystal-resonator sensors subject to heavy acoustic load" *Electron.Lett.* 36(7):610-612, 2000.

[22] Donald L.Hammond and Albert Benjaminson,"The crystal resonator- a digital transducer", *Spectrum,IEEE*, Vol.6,pp.53-58, April.1969

[23] T.H. Lee, *The design of CMOS radio-frequency integrated circuits*, New York: Cambridge University Press, 2004

[24] B.Razavi, *Fundamentals of microelectronics*, New York: John Wiley & Sons, 1997.

[25] Shih-Chang Chang, “Design of a signal processing circuit for quartz crystal microbalance biosensors”*, ASIC (ASICON), 2011 IEEE 9th international Conference* on, pp 180-183, Oct. 2011

[26] A. Arnau, Y. Jimenez and T.Sogorb, “Circuit for continuous monitoring of quartz crystal resonators in sensor applications” *Electron.Lett*. 38(8):365-367, 2002

[27]”HEF4046B MSI Phase-Locked Loop Product data sheet”, Philips Semiconductors, Nov.2011

[28] “HEF4069UB Hex Inverter Product data sheet”, Philips Semiconductors, Nov.2011