Characterization of an RF resonator to measure fluid volume for biomedical applications

CHARACTERIZATION OF AN RF RESONATOR TO MEASURE FLUID VOLUME FOR BIOMEDICAL APPLICATIONS

A Thesis by

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The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biomedical Engineering.

Kim Cluff, Committee Chair

David Long, Committee Member

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DEDICATION

I dedicate this thesis to my family, friends, and colleagues.

ACKNOWLEDGEMENTS

I would like to thank Dr. Cluff for giving me a chance working with him in his research lab. He was a friend, not only my advisor. Thank you for your support and it was my pleasure to work with you. Wish you all the best in the future.

Furthermore, I would like to thank Fayez Alruwaili and Bernardo Villafana-Ibarra for their support and leadership over the journey. Also, thank for my parents for their support and kindness, living abroad without them was not easy and I appreciate everything they did for me.

ABSTRACT

Wearable technologies have gained a huge interest in recent years due its advantages in the early diagnosis of medical conditions such as heart attack and monitoring intercranial pressure. Additionally, wearable technologies are an attractive solution in the medical field due to wearable form factor and minimal required training for uses. As such, in this study we are investigating a wearable RF skin patch resonator for the measurement of fluid volume changes. Specifically, this study aims to characterize the sensitivity, dynamic range, and repeatability of the sensor response to changes in fluid volume. The wearable skin patch sensor is an open circuit resonator that is energized wirelessly via an external antenna placed within closed proximity. Once the resonator is energized via the external antenna, it develops its own electromagnetic field and measure the changes in fluid volume nearby. For this study, we used a vector network analyzer for the purpose of energizing the wearable sensor and collecting the S_{11} return loss. From the VNA, we measure the resonance frequency shift in terms of frequency in MHz and amplitude in dB. In this study, the characterizations of the skin patch sensitivity and dynamic range were performed by dynamically increasing the fluid (H_2O) volume inside a chamber and collecting the sensor response. The result of this study illustrates that the larger square planner resonators has higher dynamic range than the others sensor designs such as triangle, circle, and pentagon while measuring fluid volume changes up to 540 mL. Furthermore, the sensitivity of large square skin patch resonator was greater than 0.75 mL. In this study, we are able to characterize the sensitivity and dynamic range of the wearable skin patch sensor which will lead into future advancement and development.

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CHAPTER 1: INTRODUCTION

1.1 Motivation

Wearable technologies have gained a huge interest in recent years due to their advantages in the early diagnosis of medical conditions such as heart attack and monitoring intercranial pressure. Furthermore, the advantages of wearable technology do not require to have invasive measurements, and this led to eliminating the risk of infection. Additionally, wearable technologies are an attractive solution in the medical field due to the wearable form factor and minimal required training for use. For example, ultrasound devices have restricted clinical settings and require training for echo personnel to demonstrate accurate measurements of cardiac function (Critchley, 2010). The focus of this study is to develop a wearable RF skin patch resonator designed for variant health field applications such as cardiac fluid volume and intracranial pressure to determine the fluid volume changes. Specifically, this study aims to characterize the sensitivity, dynamic range, and repeatability of the RF resonator sensor response to changes in fluid volume.

1.2 Objective and Specific Aims

This thesis aims to develop an RF resonator in different planar spiral such as square, triangle, pentagon, and circle to characterize the performance of each resonator for frequency, real, and imaginary data responses for the sensitivity, dynamic range, and repeatability of the fluid volume changes.

1.3 Thesis outline

1.3.1 Chapter 1 Introduces the research, aims of the study, and objective.

1.3.2 Chapter 2 Presents the literature view about wearable technology in health care and focuses on research that demonstrates the sensitivity and dynamic range.

1.3.3 Chapter 3 Present an experimental set-up for characterization of the performance of skin patch resonator in the fluid volume measurements

CHAPTER 2: LITERATURE REVIEW

2.1 Wearable Technologies

Wearable Technology is a device that is worn directly to the object to monitor, analyze, and transmit personal data. Moreover, wearable technology can be divided into two groups. The first group operate independently and serve as central connectors for other devices and information such as smartphone and wrist-worn fitness tracker. Secondary, conducting a measurement such as a pulse rate monitoring and offloading it to a major wearable device for assessment. The advantages of wearable technologies are small devices, worn directly, and remote monitoring (Godfrey, 2022).

2.2 Wearable Technology Relevant to Healthcare

Wearable technology is pivotal in healthcare to manage health issues. Wearable technology solutions could reduce the workload on medical staff and free up hospital space for more urgent or responsive care by enabling telemedicine the monitoring, recording, and transmission of physiological information from outside the hospital. Moreover, wearable technology would help to have early notice regarding health problems by monitoring the functionality of the organs in the body constantly. Nevertheless, wearable technology gained a huge interest in the medical field due to the wearable form factor and minimal required training for use (Godfrey, 2022).

The earliest wearable technology was created throughout the middle ages when spectacles were made accessible (Kasper, 2019). The first wearable timepieces appeared three centuries later, and the wristwatch was subsequently created. (Kasper, 2019). The market has expanded significantly since 2002 when Bluetooth technology enabled us to interface wirelessly with our gadgets.

Any technology integrated to create gadgets, apparel, accessories, and other items that may be easily required to wear on the body is referred to as "wearables." (Fernández-Caramés & Fraga-Lamas, 2018). Wearable technology's ability to link users to the Web and enable data transmission between a server and the gadget is one of its main benefits. The leading wearables manufacturers are Apple, Samsung, and Fitbit. For instance, in 2015, the Apple Watch was the first piece of wearable technology from Apple Inc. (Apple, 2019).

Wearable technology has provided answers to problems in the healthcare sector. These wearables' innovations brought about several advantages, including progress in patient outcomes, the standard of living, and health management. In addition, these tools give patients greater control over their health and significant access to the vast amount of data customized to each patient. (Smuck et al., 2021).

Patients with Parkinson's syndrome have had their trembling and postural issues evaluated using wrist-mounted gadgets. (Guk et al., 2019). Healthcare professionals may analyze and correlate the patient's health with the aid of these tracking devices. For individuals with illnesses besides Parkinson's, pulse rate assessment using wristbands may be helpful. For example, they may be the first to inform patients of a potential cardiogenic shock and recognize irregular heartbeats. Head-mounted gadgets, such as eyeglasses and headgear, are becoming more popular. Barometers, motion sensors, and global positioning system modules are just a few of these gadgets' many various sensors (Fernández-Caramés & Fraga-Lamas, 2018). These gadgets are designed to collect real-time health data on patients while they are engaged in various activities. In addition, digital textiles are becoming more common and include diagnostics sensors that can assess patient activity, pulse rate, and biological fluids.

Users wishing to collect health information without being distracted by bulky equipment find skin patches handier. Skin patches can have sensing devices that can guarantee direct interaction with a patient's epidermis to offer reliable information on body fluids and temperature. (Shetti et al., 2020). They can even notify people with diabetes when their blood sugar levels are excessively high or insufficient.

2.3 Introduction Radio Frequency Sensing

2.3.1 Microwave Sensing

There are two forms of microwave sensing: passive and active. Passive systems tend to catch the natural radiation emitted by the viewing surface. These systems are known for their low spatial resolution. Active systems are distinguished by their source, which can ‘light up the observed scenes regardless of the presence of the sun’ (Woodhouse, 2017). A microwave-band radio signal (the sensor transmitter) is used to record the part of the signal that is backscattered by the target towards the sensor. The power of the backscattered signal permits discrimination between distinct targets within the scene, with the distance of the target measured by the duration between the signal delivered and received. Radar is a system that uses this technique frequently. Radio Detention and Ranging is what Radar stands for. And it allows you to get a 'microwave image' of the scene you're looking at.

2.3.2 Radar Sensing

Radar sensors work by converting microwave echo signals into electrical impulses (Zou et al., 2016). Using wireless sensor technology, they identify the object's position, shape, motion characteristics, and trajectory. Unlike some of the other sensors, radar sensors are undeterred by light or darkness and may detect barriers such as glass and see-through walls. Radar can monitor greater distances than other sensors such as ultrasound and is safe for human and animals use.

The detection of motion and velocity is one of the key advantages of radar sensors over other sensors. With the use of the Dropper effect or a shift in wave frequency, a radar sensor may calculate an object's speed as well as its direction. Multi-channel sensors can also help in monitoring the target's motion from multiple angles. Complex motions are identified by inspecting the movement from several angles in addition to previously established metrics.

Radar technology is used in a range of platforms, but the most prevalent are CW Doppler and FMCW radar sensors. Doppler radars are highly specialized radars that use Doppler effects to calculate a target's speed at varying distances. FMCW Radar sensors are used to calculate the distance between two points. The FMCW's frequency, with exception of Doppler Radar, fluctuates over time as per the law of triangular waves (Yuan et al., 2019). Radar sensor technology is used in a wide range of applications from missile guidance to medical equipment such as detecting human vital signals (Kuo & Lin, 2016). However, the limitation of the measurement method of Doppler radar is complicated, noise in the system, and a large form factor.

2.3.3 Far-Field Near Field Radio Frequency

Near-field non-radiative behaviors take precedence close to the antenna, while far-field electromagnetic wave behaviors take precedence at increasing distances. As the distance between the sources grows, the far-field electric and magnetic forces decrease, resulting in an inverse-square rule to the maximum transmission concentration of electromagnetic radiation (Jones, Hamlyn, and Vaughan, 2010). Furthermore, the strengths of near-field electric and near-field magnetic forces tend to decrease with increasing distance.

The far field is the region of electromagnetic radiation that behaves normally. Magnetic fields having electric dipole properties are well-dominant. The multiple-type fields, which are classified as a group of dipoles with a defined phase connection, govern the near field. The two boundary zones have a fuzzy definition that is determined by the dominant frequency of the source and the size of the radiation pattern. The emitted power of an antenna decreases as a function of distance, whereas absorbed radiation does not provide feedback to emitters in the far-field zone. The load of the emitter is affected by radiation absorption in the near-field area. Magnetic induction can be seen, for example, in a transformer. The proportion of electric and magnetic base intensity is essentially the medium's trend susceptibility, with each component of the electric and magnetic fields connected to a change in the other. Electric and magnetic fields can coexist in the near-field area, with one overpowering the other in different subspaces. In the near-field area, a dipolar source would produce solid electromagnetic current and diffident magnetic fields

2.4 Applications of Non-Invasive RF Sensors Sensitivity, Dynamic Range, And Repeatability Related to Fluid Volume Changes.

There are huge applications related to wearable technologies such as ECG, measuring blood oxygen levels, skin temperature sensors, and monitoring stroke volume in the heart (The times of India, 2020). Those technologies are helpful to monitor the functionality of the organs inside the body by characterizing the fluid volume changes. The non-invasive procedure is common these days due to the safety of the patients. Moreover, it describes treatments in the medical field without breaking the skin (Libraries, 2017).

2.4.1 Sensitivity:

Sensitivity is defined as the smallest change that the sensor could detect. The sensitivity represents the slope corresponding to the effective permittivity and the fluid volume changes. The importance of the sensitivity is to determine how large the amplifications are between the sensor and the object. In order to have desirable wearable technology, the sensor should have a high sensitivity towards small fluid volume changes to monitor the functionality of the organs inside the body such as pulse rate, and intracranial pressure (Team, 2021).

Currently, the research presented 'A Patch Resonator for Sensing Blood Glucose Changes' focuses on the sensitivity changes in the blood tissue of a realistic human body. The methodology of the study is to characterize the frequency response by examining a realistic digital human phantom called Hugo. Moreover, the patch resonator was placed in Hugo's arm to keep the superstrate at the minimum possible thickness and the resonance frequency was operated at 2.235 GHz and the permittivity of the blood is 58.26. After that, the permittivity was changed from 58.26 to 54.76. The result demonstrates that the frequency patch did not change until the permittivity reach 55.26 due to the low-quality factor of the resonator and small changes in the permittivity. The resonance frequency was shifted from 2.235 GHz to 2.232 GHz. The presented study concluded that the patch resonator showed sensitivity to glucose fluid changes which correspond to the changes in the permittivity of the blood (Yilmaz, 2014).

Moreover, another study focuses on the sensitivity of heart rate monitoring by using flexible wearable technology during sleep. The sensor was designed as an inverted-F antenna (PIFA) structure and wrapped around the wrist to adjust the sensor in the radial artery. The result demonstrates that the heart rate significantly decreased during sleep. Furthermore, measuring the heart rate from the radial artery is 95% accurate compared with the EEG headband. The presented study concluded that the RF resonator can measure the heartbeat and could be useful for detecting long-term monitoring due to being a less intrusive measurement method (Kim, 2022).

Additionally, the research investigated the sensitivity of bioimpedance to monitor thoracic fluid in heart failure patients. Bioimpedance is used to monitor the functionality of the organ by characterizing the fluid volume changes inside the body. The experiment was done by monitoring the posture changes which are supine, legs raised posture, standing, and sitting. This led to the study of the sensitivity performance of the device by detecting the thoracic fluid. The result for posture changes demonstrates that there is a variation different in the vascular fluid redistribution and shows the higher value of fluid in the recumbent body positions compared to the erect thorax. (Dovancescu, 2013).

The fluid volume sensitivity measurements were done in our lab in past years. The sensitivity was tested by using the relationship between the fluid volume changes and the frequency shift. The model consisted of an empty 100 ml chamber and used water to demonstrate the sensitivity with increments of 0.5 mL, 1 mL, 10 mL, and 20 mL. The experiments illustrated that when the volume was increased, there were changes in the effective permittivity of the sensor (Alruwaili, 2019).

2.4.2 Dynamic Range:

Dynamic range describes the highest point and lowest points at which the sensor continues reading the fluid volume changing inside the body. Also, it specifies the value or range of acceptable values that a dynamic signal can assume when delivered or generated to a particular system. Moreover, the dynamic range represents the upper and lower limits of the signals by continuous variation of input and output (Circuit, 2020). The importance of the dynamic range is to identify the range that the sensor could detect inside the body to ensure collecting the changing of the fluid volume changes from the organ’s functionality (Group, 2017).

Currently, the research “Noninvasive Glucose Sensing in Aqueous Solutions Using an Active Split-Ring Resonator” focused on monitoring glucose in serum concentration by using microwave sensors. The result shows that the microwave sensors can be used to monitor the glucose in serum concentrations by studying the resonant frequency shifting with glucose level concentrations change within 100-1000 $mMol.L^{-1}$. Moreover, the correlation between resonance frequency and glucose level performs linearly with changing the concentration of glucose from low to high (Abdolrazzaghi, 2021).

Another research uses a flexible skin patch sensor to monitor limb hemodynamics and morphology associated with blood flow. The research experimental setup was using the arm phantom by placing the skin patch sensor in the radial location to detect the fluid flow. In the beginning, they used a beaker to study the correlation between the fluid volume change and the resonant frequency within 0 to 100 mL. After that, the pulse flow detection was monitored by studying the amplitude (S_{11}) and pulsatile flow correlation inside the arm phantom at 26 MHz. This would provide a conclusion to characterize subjective limb hemodynamics and demonstrate that the electromagnetic sensor could detect the biofluid phenomena (Mohammed et al., 2019).

2.4.3 Repeatability

For sensors, repeatability is the consistency of the sensor's results against itself; it is a sensor's ability to give similar outputs for identical inputs (Elsevier B.V.). In engineering, repeatability is essential, especially where precision tests/measurement matters. First, repeatability for sensors ensures result consistency. When tests or measurements are required in a project, engineers apply repeatability to identify result variations and the causes. Second, repeatability enhances the reliability of the outcome. When a test is repeated severally using the same sensor gadget, under the same variables, and a constant variation within the accepted range is realized throughout, it is an indication that repeatability results can be relied on. The same sensor's results in repeated tests guarantee some sense of accuracy, making repeatability a reliable aspect of engineering.

Repeatability is also relevant in wearable technology in healthcare. Wearable such as wrist wearables, smartphone apps, abdominal wearables, ingestible sensors, etc., allows patients to continuously monitor their health by doing repeated checkups at a given time. Also, they allow repeatability tests for self where patients easily collect repeated data on their health which healthcare providers use for their diagnosis and treatment (Khattak). With repeatability, patients can collect as much data as possible on their physiological parameters, identify the variation in data outcome and decide whether professional consultation is required.

CHAPTER 3: CHARACTERIZATION OF AN RF RESONATOR TO MEASURE FLUID VOLUME FOR BIOMEDICAL APPLICATIONS

3.1 Introduction

Wearable technologies have gained a huge interest in recent years due to their advantages in the early diagnosis of medical conditions such as heart attack and monitoring intercranial pressure. The performance of wearable technology is important due to have accurate data can be used to better inform clinical decisions. This research focuses on three main categories which are sensitivity, dynamic range, and repeatability. The sensitivity is the smallest change that the sensor can detect. The dynamic range is the highest signal can the sensor detect. The repeatability is to characterize the performance output from the sensor by repeating the experiment several times in order to ensure have similar outcome under the same conditions (Godfrey, 2022).

The passive sensor is a structure of a circuit that performs without needing for controlling magnetic and electrical sources. The components of the passive sensor may be composed of lumped elements which are resistors, inductance, and capacitors. The design of the passive sensor is important because it would affect the function parameters such as the frequency, amplitude level, and phase shift. Furthermore, the quality factor is the system that remains its total energy constantly at all conditions while taking the reading from the object (Vahldieck, 2022).

The interesting of using wearable technology is to measure the fluid volume changes inside the body, such as stroke volume and intracranial pressure. Stroke volume is the volume of the blood that is injected from the heart into the body during contraction. Moreover, the term "LVSV" refers to the blood that the left ventricle (LV) expels on an average of about 80 mL every cardiac cycle in healthy people. Medical professionals may accurately forecast heart problems and carry out the necessary medical action if LVSV is measured early in medical exams (Alruwaili, 2019).

On other hand, Intracranial pressure is increasing the pressure around the brain due to increasing the amount of fluid. Most humans have a compensating reserve that enables intracranial volume increases of 60 to 80 mL with only modest pressure increases (Griffith, 2018). The research focused on the characterization of the skin patch resonator performance by studying the sensor in different ways such as sensor design, trace width, gap width, size, and shape the sensor. Moreover, the purpose of the research is to determine which sensor has the best sensitivity and dynamic range by characterizing the resonant frequency with fluid volume changes. This would be helpful to have a point of view for monitoring health care by using wearable technologies.

3.2 Material and Methods

The RF skin patch resonant frequency was built using a conductive material, a copper foil sheet, into a different planar spiral with extensive inherited inductance, representing the number of turns with trace width and gap width. The wearable skin patch sensor is an open circuit resonator that is energized wirelessly via an external antenna placed within closed proximity. The sensor has three main parameters which are resistance, capacitance, and inductance. The loop antenna surrounded the sensor to radiate the resonance frequency waves and the S_{11} reflection coefficient. Once the resonator is energized via an external antenna, it develops its own electromagnetic field and measures the fluid volume changes nearby (Szatkowski, 2014).

The sensors were used for data collection for sensitivity, dynamic range, and repeatability. There were four different shapes designed as an original model to characterize the performance of the resonant frequency response to fluid volume changes in a chamber. The four designed shapes were square, triangle, circle, and pentagon with three different sizes such as large, medium, and small as shown in the tables 3.1, 3.2, 3.3, 3.4 and figure 3.1.

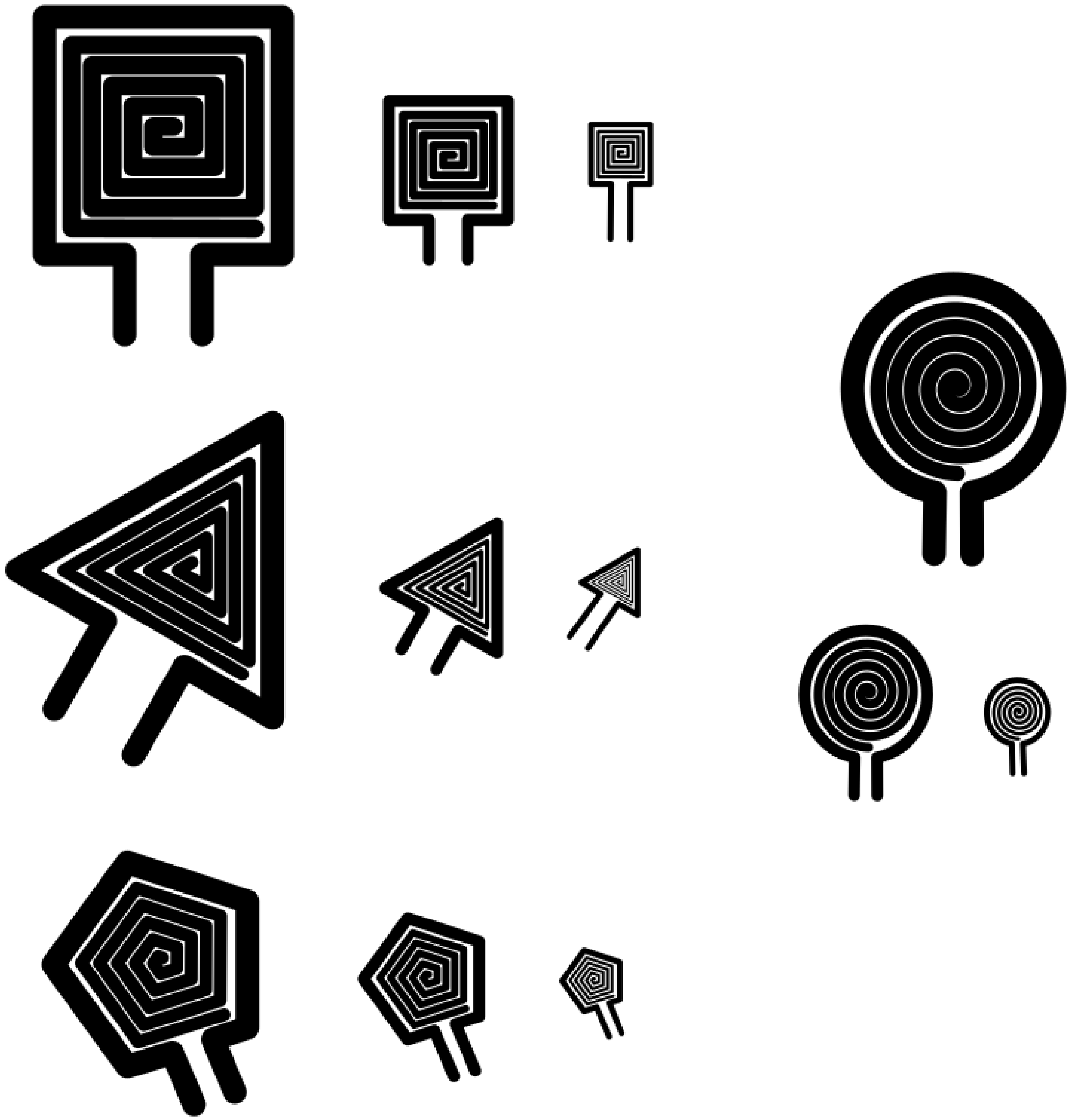


Figure 3.1: Illustrate the sensor designs for different shapes such as square, circle, triangle, and pentagon with various sizes such as large, medium, and small.

Table 3.1: Illustrate the dimensions for square sensors design such as large, medium, and small.

Square Shapes	Dimensions (mm)	Surface Area of the Sensor (mm^2)	Surface Area of the Spiral (mm^2)	Trace Width (mm)	Gap Width (mm)
Large	30 x 40	1200	683	2.2	0.20
Medium	15 x 20	300	148	1.02	0.20
Small	7.5 x 10	75	28	0.41	0.20

Table 3.2: Illustrate the dimensions for triangle sensors design such as large, medium, and small.

Triangle Shapes	Dimensions (mm)	Surface Area of the Sensor (mm^2)	Surface Area of the Spiral (mm^2)	Trace Width (mm)	Gap Width (mm)
Large	30 x 39	585	387	1.39	0.20
Medium	15 x 19	142	62	0.68	0.20
Small	7.5 x 9.6	36	9.5	0.21	0.20

Table 3.3: Illustrate the dimensions for pentagon sensors design such as large, medium, and small.

Pentagon Shapes	Dimensions (mm)	Surface Area of the Sensor (mm^2)	Surface Area of the Spiral (mm^2)	Trace Width (mm)	Gap Width (mm)
Large	30 x 40	1500	300	1.84	0.20
Medium	15 x 18.2	341	113	1.02	0.20
Small	7.5 x 11	103	17	0.40	0.20

Table 3.4: Illustrate the dimensions for circle sensors design such as large, medium, and small.

Circle Shapes	Dimensions (mm)	Surface Area of the Sensor (mm^2)	Surface Area of the Spiral (mm^2)	Trace Width (mm)	Gap Width (mm)
Large	30 x 28	706	334	2.42	0.20
Medium	15 x 17.5	176	133	1.13	0.20
Small	7.5 x 8.8	44	33	0.47	0.20

For this study, we used a vector network analyzer to energize the wearable sensor and collect the S_{11} return loss. From the VNA, we measure the resonance frequency shift in terms of frequency in Hz and amplitude in dB. In this study, the characterizations of the skin patch sensitivity and the dynamic range were performed by dynamically increasing the fluid (H_2O) volume inside a chamber and collecting the sensor response as shown in Figure 3.2.

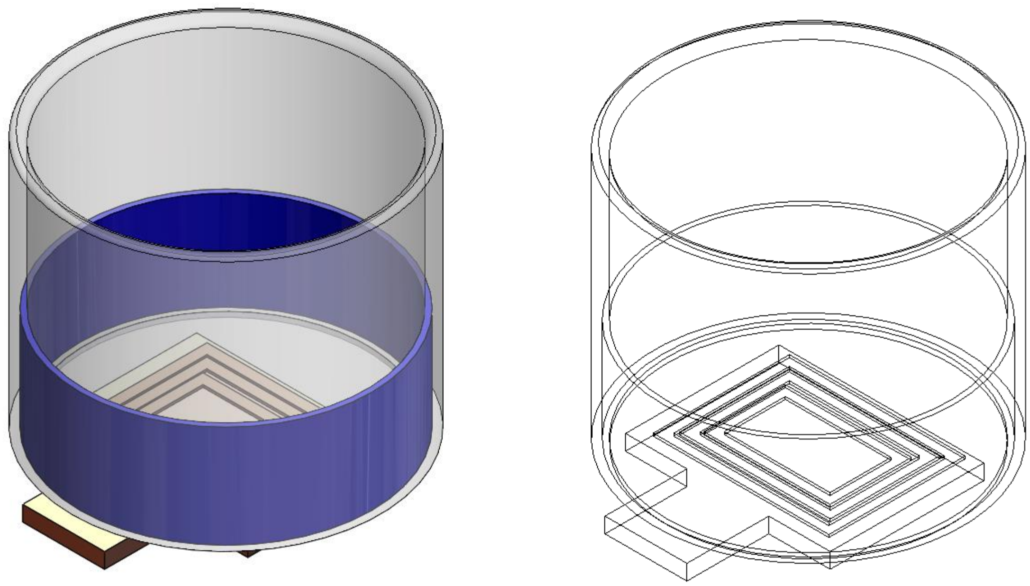


Figure 3.2: Illustrates the experimental setup for collecting the data.

3.2.1 Protocol for Making Sensors

The sensor design protocol was done using MATLAB code, the Inkscape software, and the etching process. The MATLAB code was used to have the sensor design with specific parameters such as shape, gap width, trace width, and the number of turns. Since the study was focused on the characterization of the sensor, we tried to keep everything constant with four number of turns and 0.20 ml for the gap width to study the sensor's performance. After that, the sensor's design was transferred to the Inkscape software to adjust the design and print it on the foil copper sheet. The copper foil sheet is self-adhesive, and the width of the copper was 0.03175 mm. The copper sheet was placed in the printer to print the sensor design by using the ink. Furthermore, the etching process is important to remove the copper that surrounded the ink using Ferric Chloride (FeCl3).

3.2.2 Fluid Volume Sensitivity Measurements

The volume sensitivity measurements were selected to characterize the performance of the resonant frequency response to fluid volume changes in a chamber. The sensors were placed below the empty 100 ml chamber to characterize the sensitivity performance. Inside the chamber, the water was added with 4 ml as a base to avoid the permittivity of the air and after that added increments of 1 mL, 0.75 mL, 0.5 mL, and 0.25 mL were used to characterize the sensitivity.

3.2.3 Fluid Volume Dynamic Range Measurements

The dynamic range measurements were selected to characterize the performance of the resonant frequency response to fluid volume changes in a chamber. The sensors were placed below multiple empty chambers which are 1000 ml, 500 ml, and 250 ml in order to characterize the resonant frequency assessments. Also, the skin patch resonators were placed below the beaker to study the dynamic range with increments of 40 mL to illustrate the highest resonance frequency signal.

3.2.4 Fluid Volume Repeatability Measurements

The repeatability process is to study the measurements of sensitivity and dynamic range multiple times. The first experiment designed for sensitivity and dynamic range was repeating the measurements without changing the positions of the sensor and the chamber. The second study is to remove the sensor and placed it back again below a chamber to study if there is a change in the measurements.

3.2.5 Signal Processing

Signal processing was done to characterize the sensor performance to fluid volume change in the chamber. The resonance frequency was tracked on each sweep and analyzed to study the significant difference between the fluid volume changes. MATLAB was used to create the program for analyzing the sensitivity and dynamics ranges data. Moreover, the ANOVA test was used to characterize the sensitivity of the fluid volume changes and study the significant differences to determine if there is a relationship between the resonance frequency and fluid volume changes.

3.3 Results

At the beginning, all the sensors' shapes were tested to determine the starting point of the resonance frequency and the highest amplitude. The amplitude is important due to illustrating how much the sensor transmits signals to the chamber as shown in the table below.

Table 3.5: Illustrate the highest resonance frequency with amplitude.

Sensor' Shape	Amplitude (dB)	Resonance Frequency (MHz)
Large Circle	-3.0	480
Medium Circle	-1.2	230
Small Circle	-1.0	240
Large Pentagon	-3.0	530
Medium Pentagon	-1.0	260
Small Pentagon	-1.0	260
Large Square	-7.0	320

Table 3.5 (continued)

Medium Square	-1.0	230
Small Square	-1.0	260
Large Triangle	-4.0	390
Medium Triangle	-1.2	250
Small Triangle	-0.8	280

From the table, the large square sensor has the highest amplitude which is -7 dB. The medium and small shapes for all shapes were ignored due to the performance of the amplitude which is smaller than -3 dB. Since the sensors that are smaller than -3 dB will cause noise and we cannot depend on these sensors to take the measurements because it carries a small amount of energy that transmits to the beaker study.

3.3.1 Sensitivity

The sensitivity study was conducted to characterize the sensor performance to determine the smallest change that the sensors can detect. This was achieved by studying the different fluid increments and the correlation between frequency shift and fluid volume changes. We performed an ANOVA test to demonstrate the correlation. The medium and small sensor shapes were not showing any relationship between fluid volume changes and resonance frequency due to having low amplitude. Figures 3.3, 3.4, 3.5, 3.6 illustrate the sensitivity of the large square, circle, triangle, and pentagon spiral shapes for resonance frequency shift. The x-axis displays the change in resonance frequency between the increments and the y-axis is the increments of fluid volume changes. The blue circle in each figure represents the starting point of 1 mL and shifts to the left with changing the fluid. In each measurement, the mean and standard deviation are illustrated at each measure since we collected the data 10 times. The results indicate that there was a significant difference between the frequency shifts with each volume increment which concludes the sensitivity for large square, circle, and triangle. However, the large pentagon did not show any correlation between the fluid volume changes and resonance frequency.

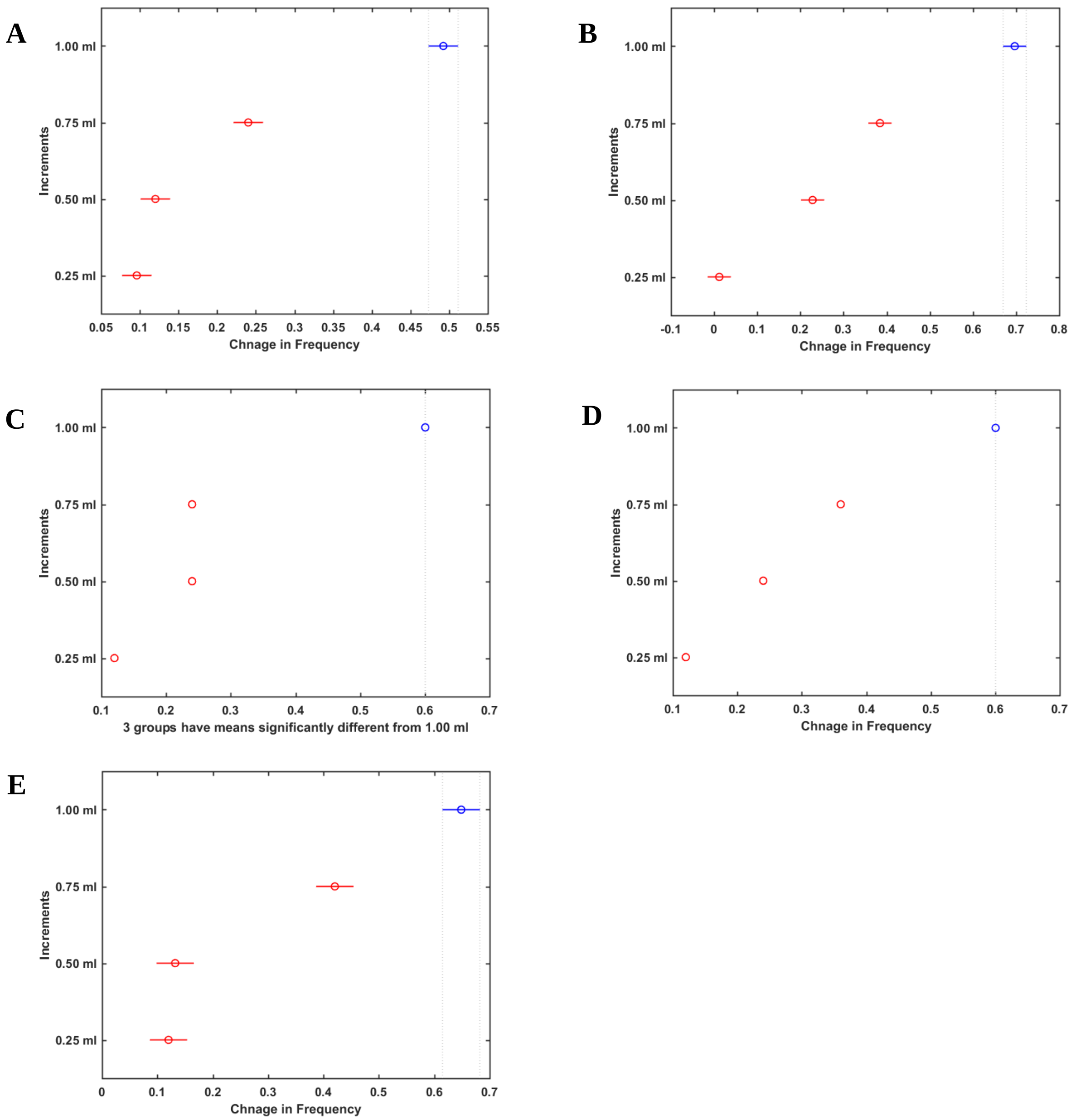


Figure 3.3: Shows five studies for characterizing the sensitivity of large square shapes to illustrate the correlation between the fluid volume changes and resonance frequency. The result in figures B and D indicate that the sensitivity is greater than 0.75 mL.

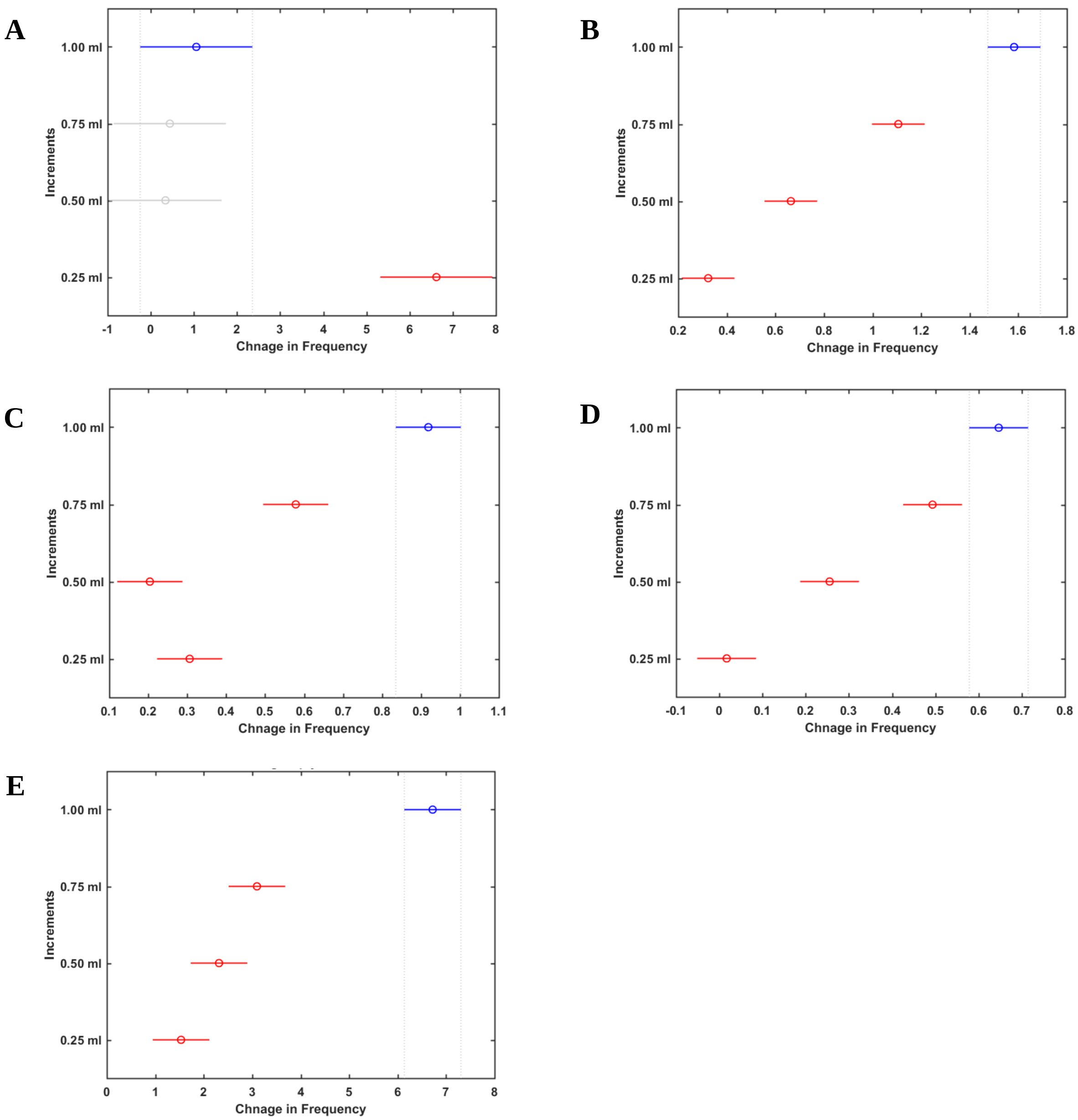


Figure 3.4: Shows five studies for characterizing the sensitivity of large circle shapes to illustrate the correlation between the fluid volume changes and resonance frequency. The result indicates that the sensitivity is greater than 1 mL.

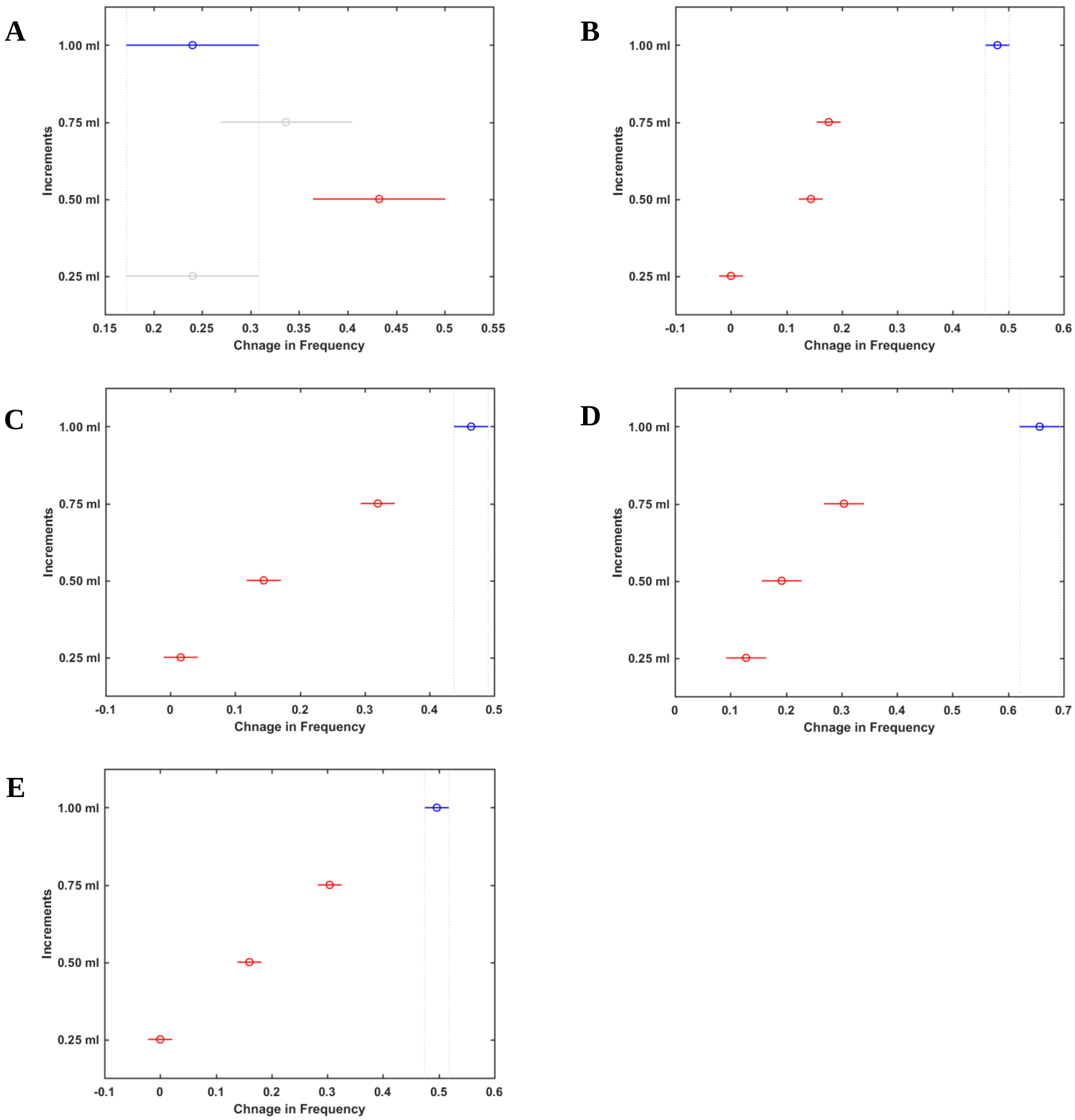


Figure 3.5: Shows five studies for characterizing the sensitivity of large triangle to illustrate the correlation between the fluid volume changes and resonance frequency. The result indicates that the sensitivity is greater 1 mL.

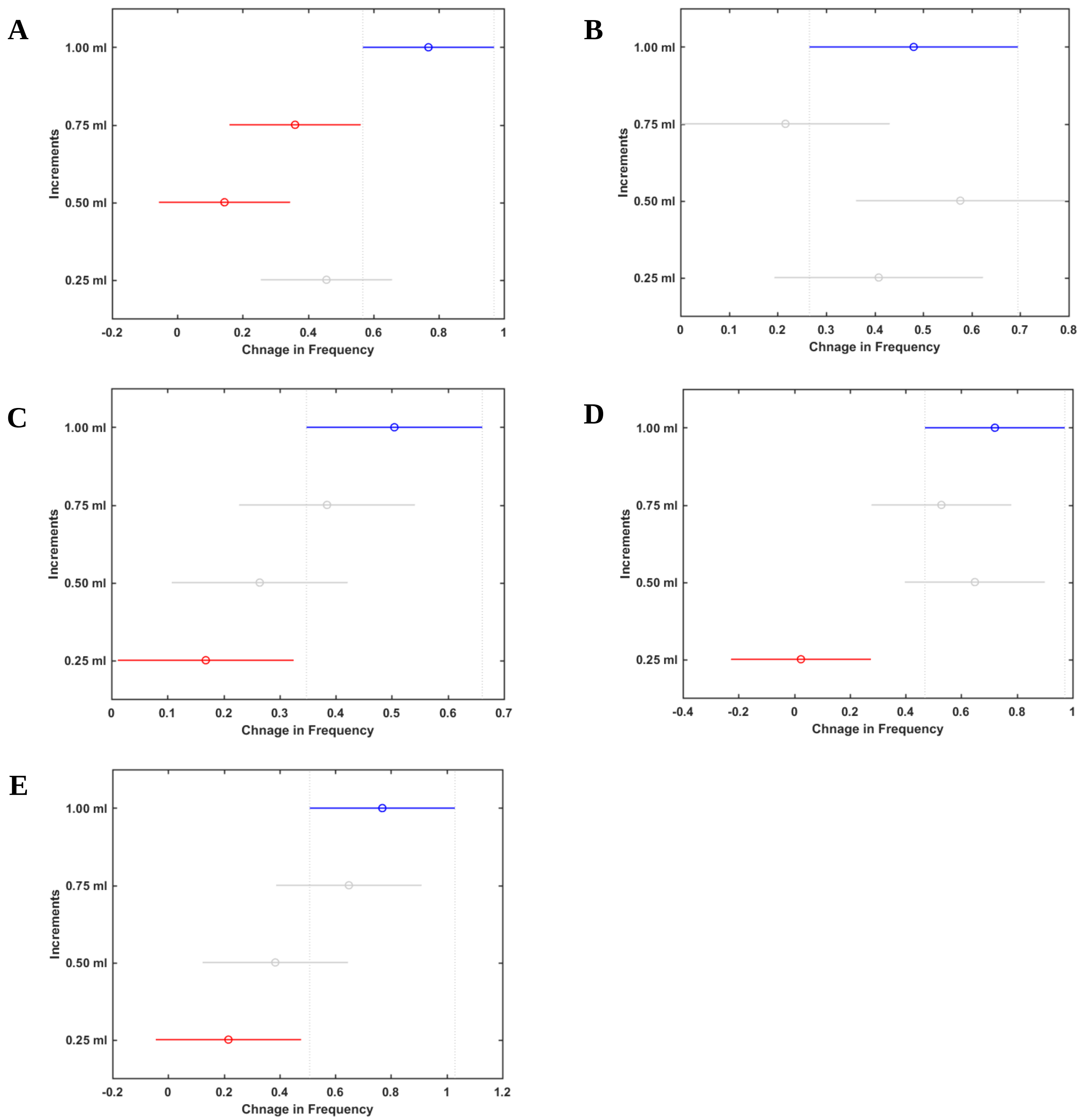


Figure 3.6: Shows five studies for characterizing the sensitivity of large pentagon shapes to illustrate the correlation between the fluid volume changes and resonance frequency. The result indicates that there is no significant difference.

3.3.2 Dynamic Range

The dynamic range study was conducted to characterize the sensor performance due to the different fluid increments to determine the highest signal resonance frequency could the sensor detect as shown in the figures below. This was achieved by studying the different fluid increments and the correlation between frequency shift and fluid volume changes. We performed a MATLAB code to demonstrate the correlation by tracking the peak of the resonant frequency as shown in the figures below.

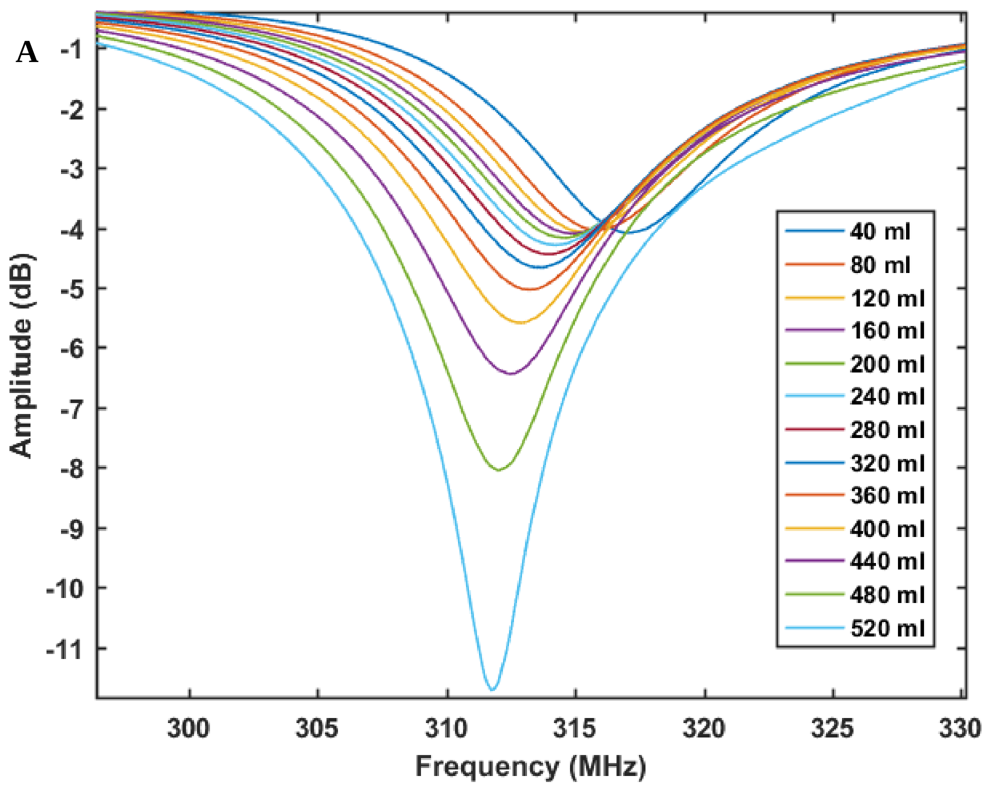
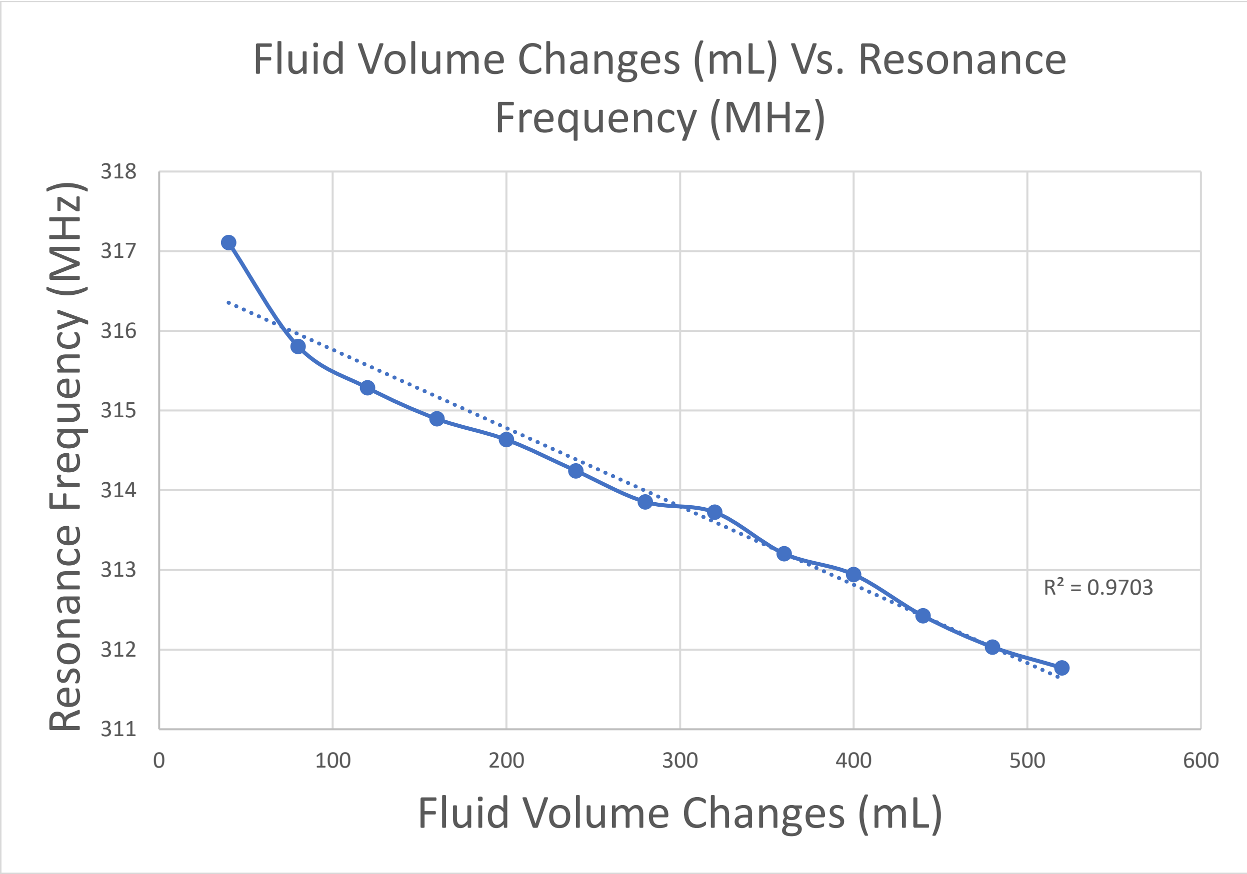


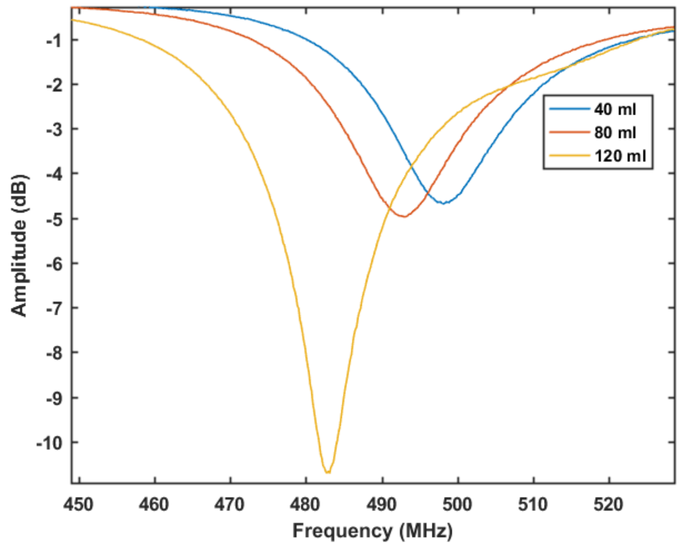
Figure 3.7: A) Presents the resonance frequency shift in the large square sensor design as fluid volume increased by increments 40 mL. B) Shows the relationships between the principal resonant frequency and fluid volume shifts illustrate a strong correlation ($R^2 = 0.97$).

Figure 3.7 (continued)

B



A



B

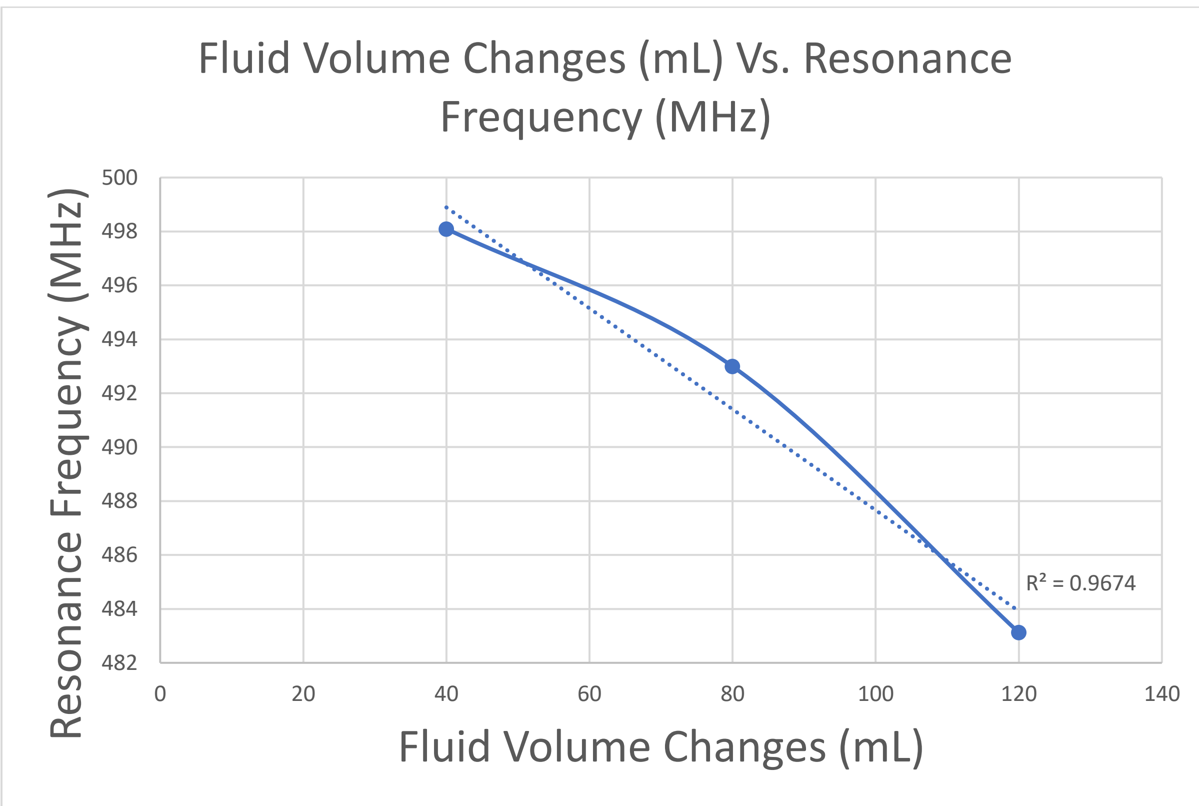
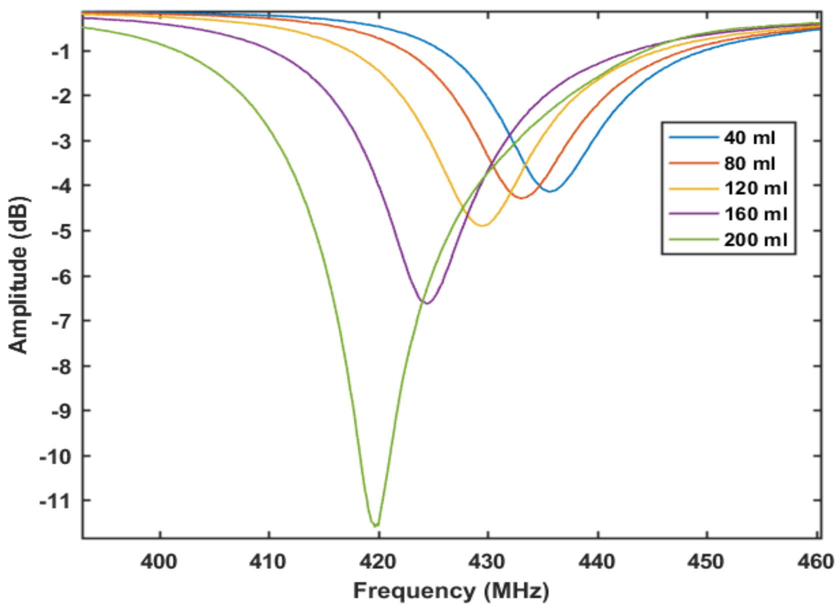


Figure 3.8: A) Presents the resonance frequency shift in the circle square sensor design as fluid volume increased by increments of 40 mL. B) Shows the relationships between the principal resonant frequency and fluid volume shifts illustrate a strong correlation (R^2 = 0.96).

A



B

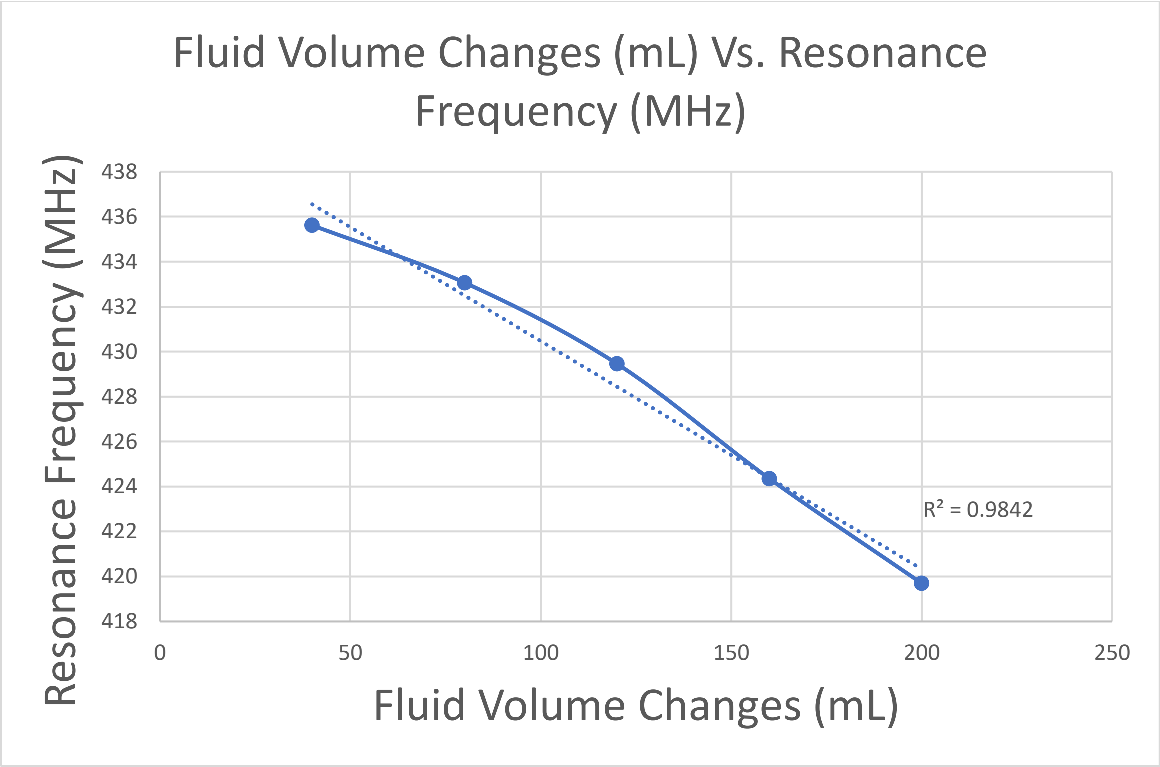
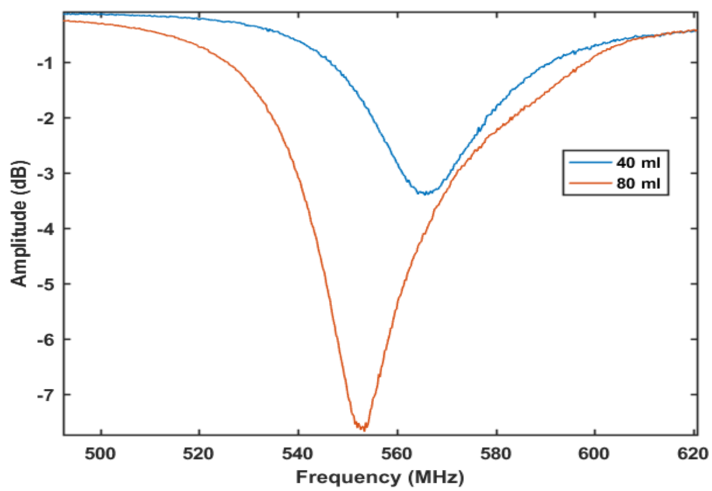


Figure 3.9: A) Presents the resonance frequency shift in the large triangle sensor design as fluid volume increased by increments 40 mL. B) Shows the relationships between the principal resonant frequency and fluid volume shifts illustrate a strong correlation (R^2 = 0.98).

A



B

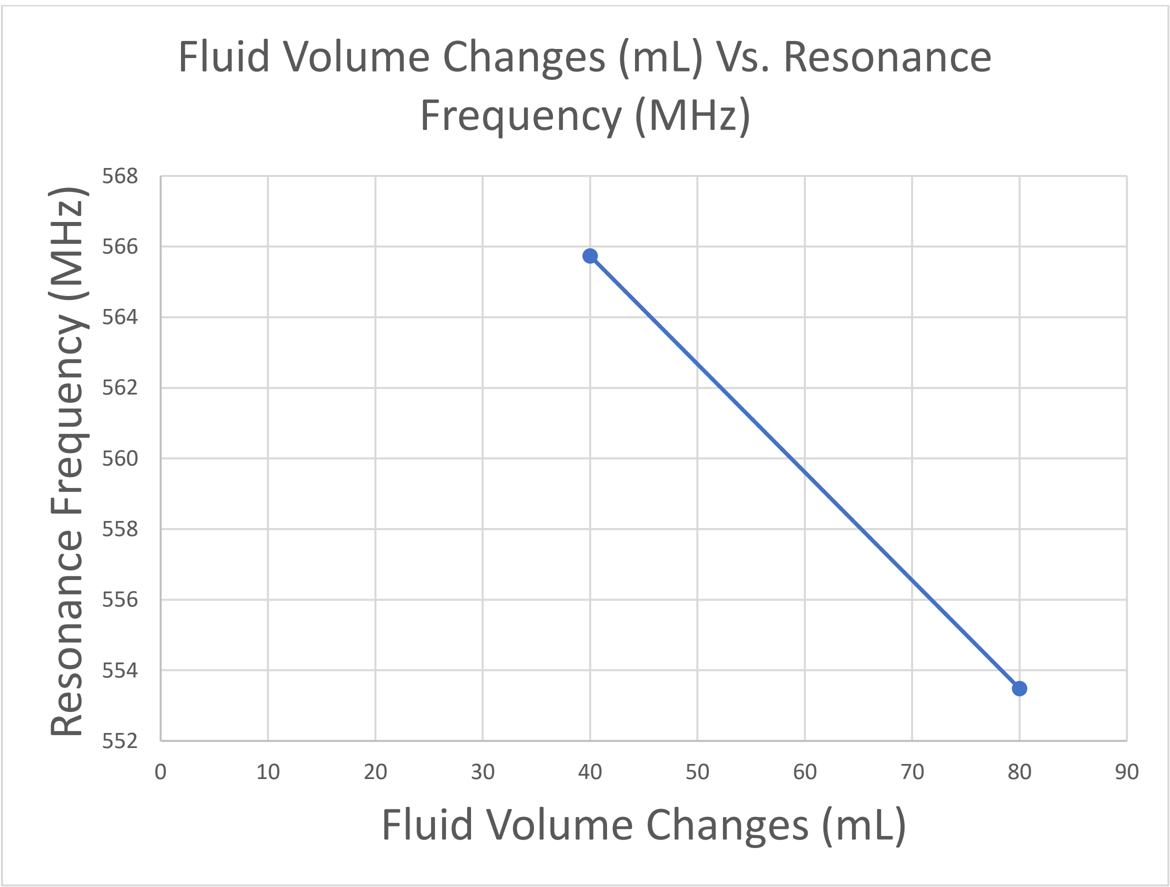


Figure 3.10: A) Presents the resonance frequency shift in the large pentagon sensor design as fluid volume increased by increments of 40 mL. B) Shows the relationships between the principal resonant frequency and fluid volume shifts.

3.3.3 Phase Shift

A relative permittivity is a complex number that represents real and imaginary data. The imaginary data correspond to an electrical field and the real data correspond to magnetic field. Furthermore, The phase shift indicates the phase difference between the imaginary output over the real output. The figures illustrate the phase shift when the resonance frequency reaches the peak in each fluid volume change.

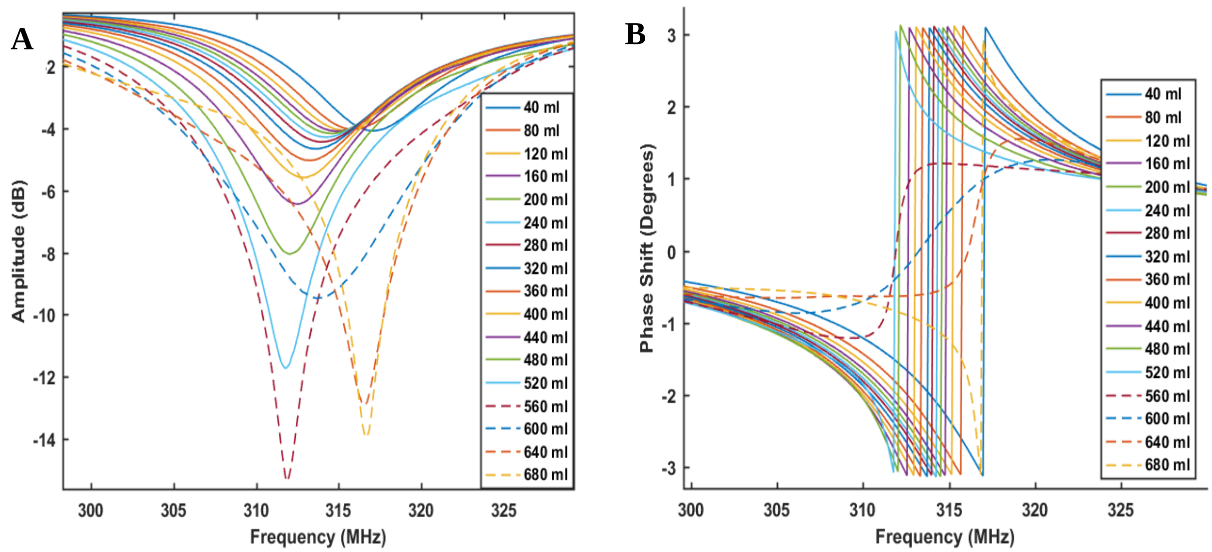


Figure 3.11: A) Shows the resonance frequency shift in the large square sensor design as fluid volume increased by increments of 40 mL and started shifting back over 520 mL. B) Shows the phase shift.

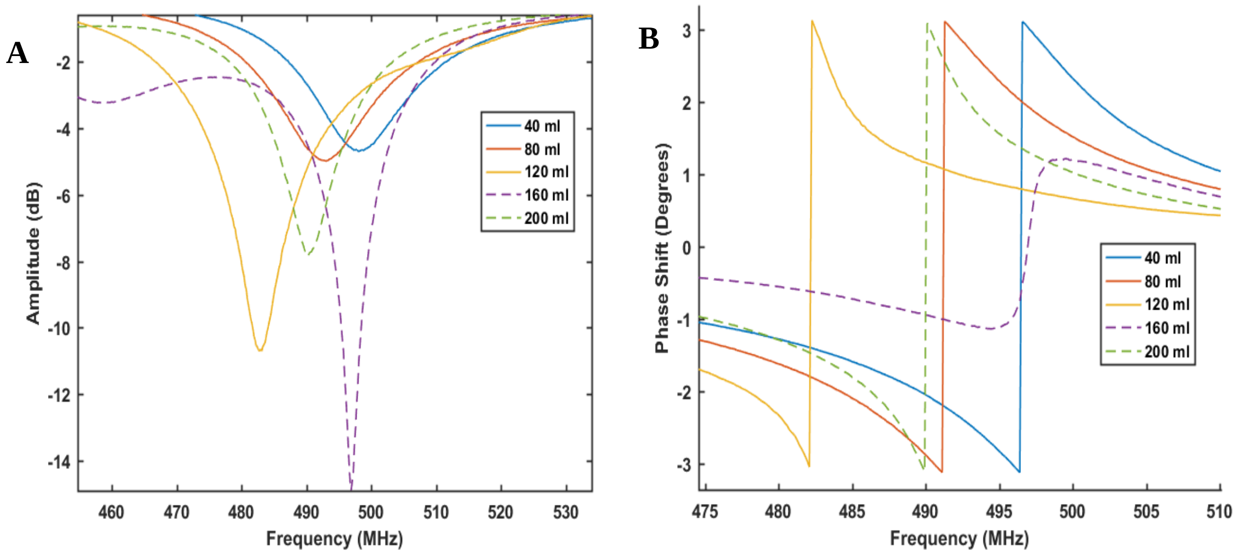


Figure 3.12: A) Shows the resonance frequency shift in the large square sensor design as fluid volume increased by increments of 40 mL and started shifting back over 120 mL. B) Shows the phase shift.

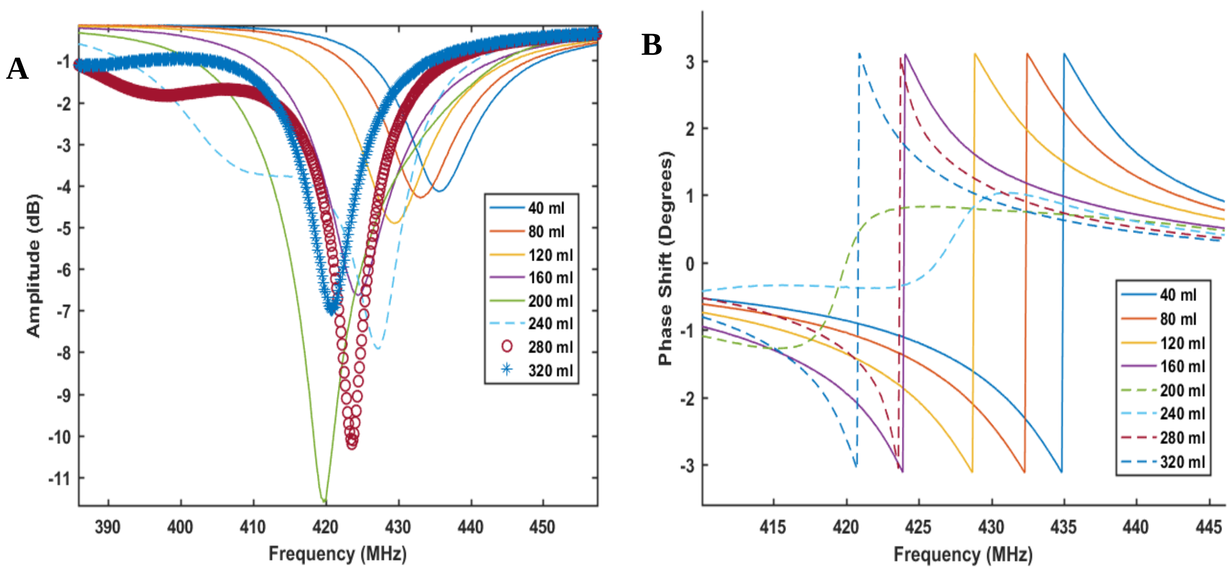


Figure 3.13: A) Shows the resonance frequency shift in the large square sensor design as fluid volume increased by increments of 40 mL and started shifting back over 200 mL. B) Shows the phase shift.

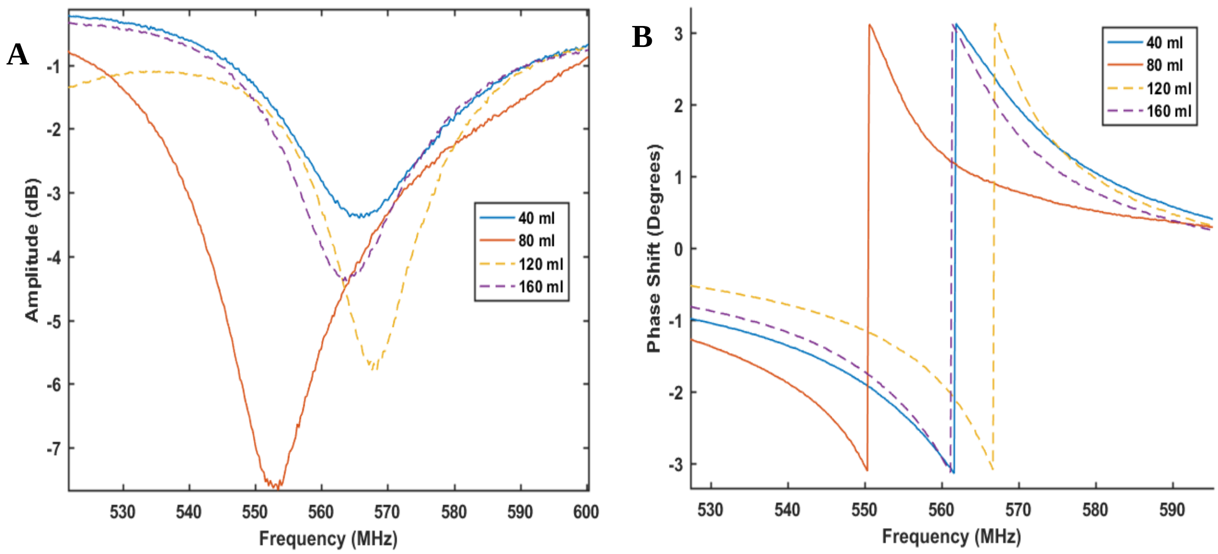


Figure 3.14: A) Shows the resonance frequency shift in the large pentagon sensor design as fluid volume increased by increments of 40 mL and started shifting back over 80 mL. B) Shows the phase shift.

3.3.4 Repeatability

The large square skin patch resonator has been characterized in different sizes of beaker such as 100, 250, 500, and 1000 mL to study each resonant frequency respectively. The result shows there is no change in the resonant frequency as shown in the figures below.

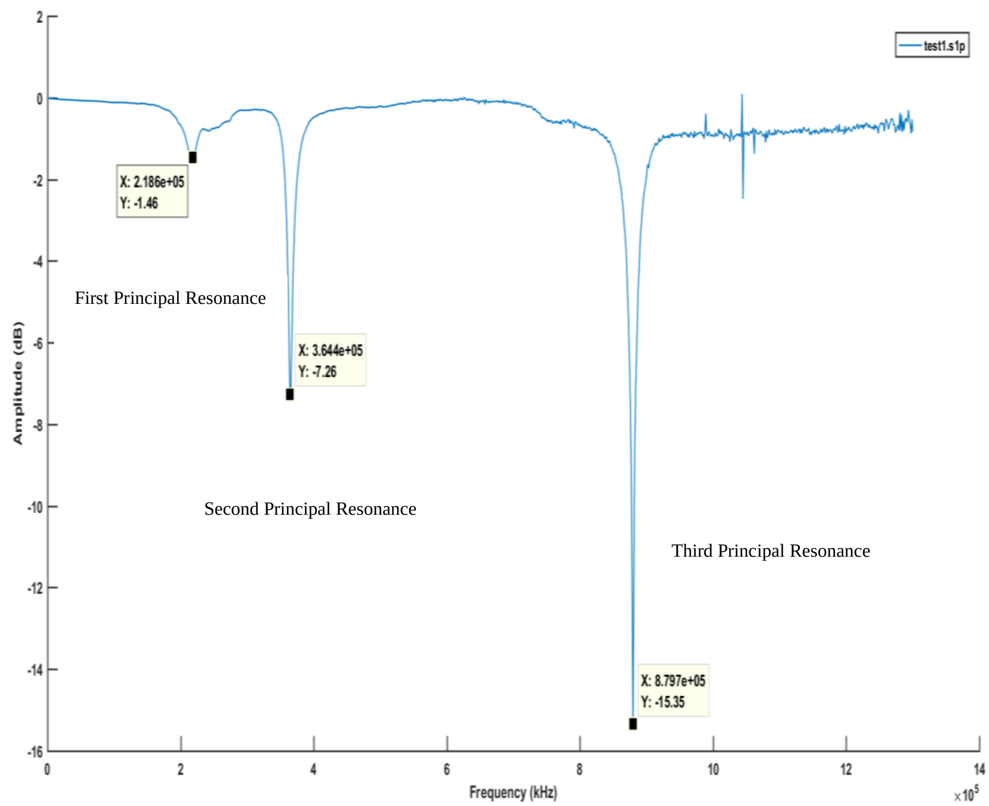


Figure 3.15: Illustrate the resonance frequency for a large square sensor was placed below the 100 mL empty chamber. The resonance frequencies are 2.1 MHz, 3.6 MHz, 8.8 MHz respectively.

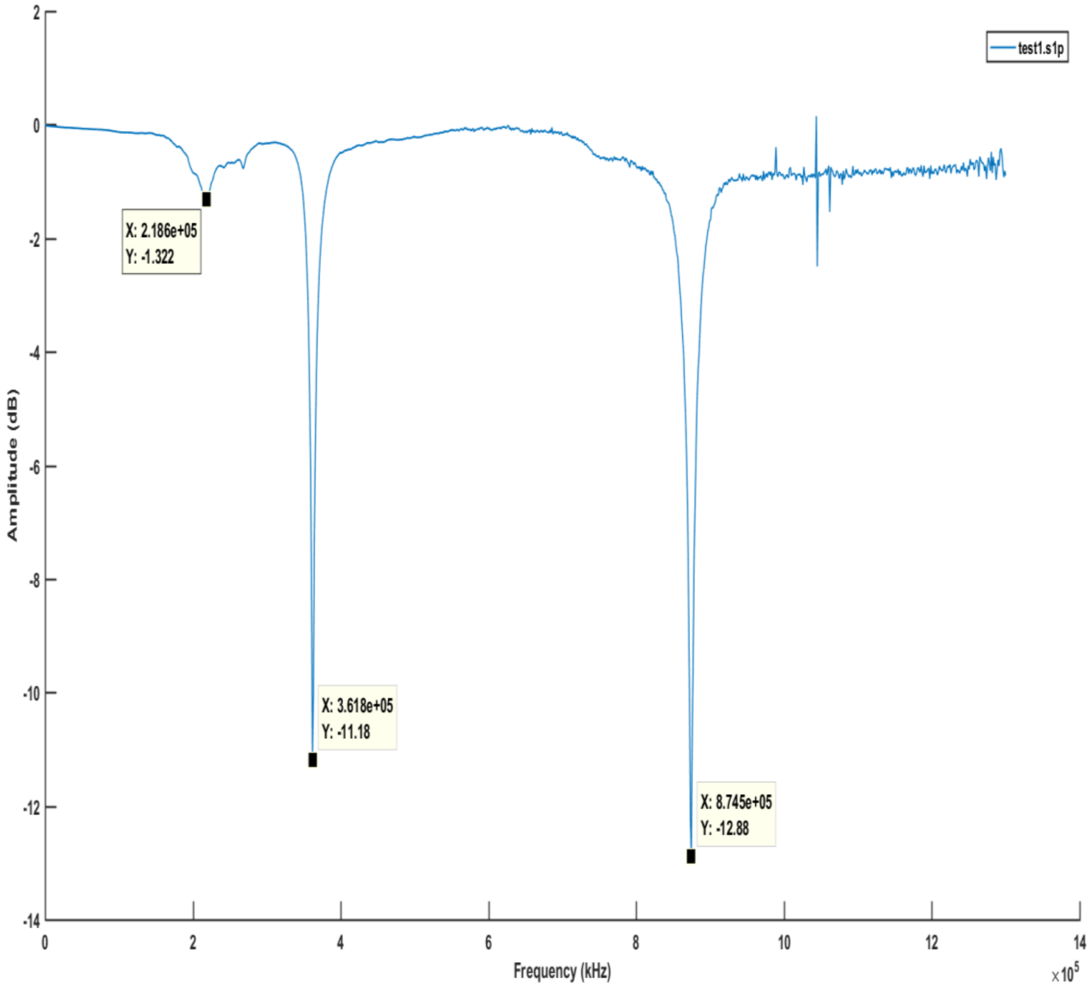


Figure 3.16: Illustrate the resonance frequency for a large square sensor was placed below the 250 mL empty chamber. The resonance frequencies are 2.2 MHz, 3.6 MHz, 8.7 MHz respectively.

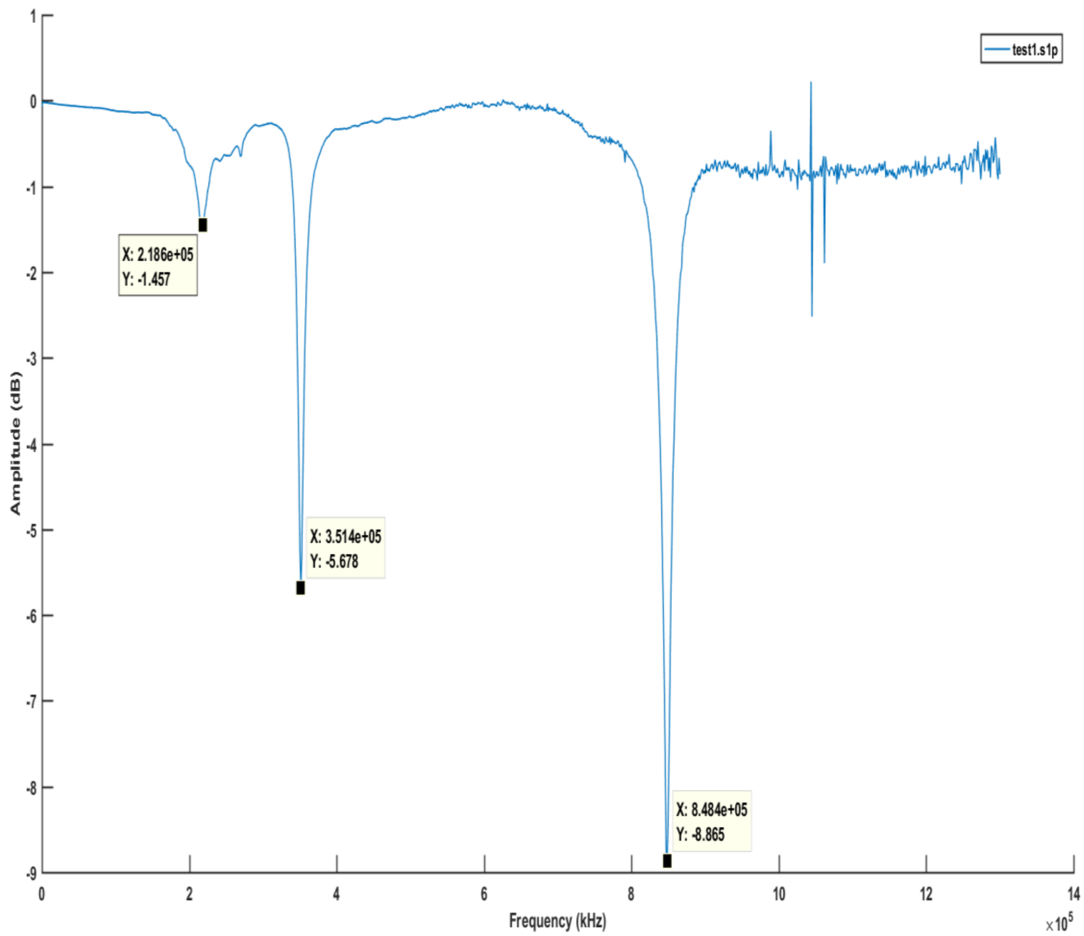


Figure 3.17: Illustrate the resonance frequency for a large square sensor was placed below a 500 mL empty chamber. The resonance frequencies are 2.1 MHz, 3.5 MHz, 8.5 MHz respectively.

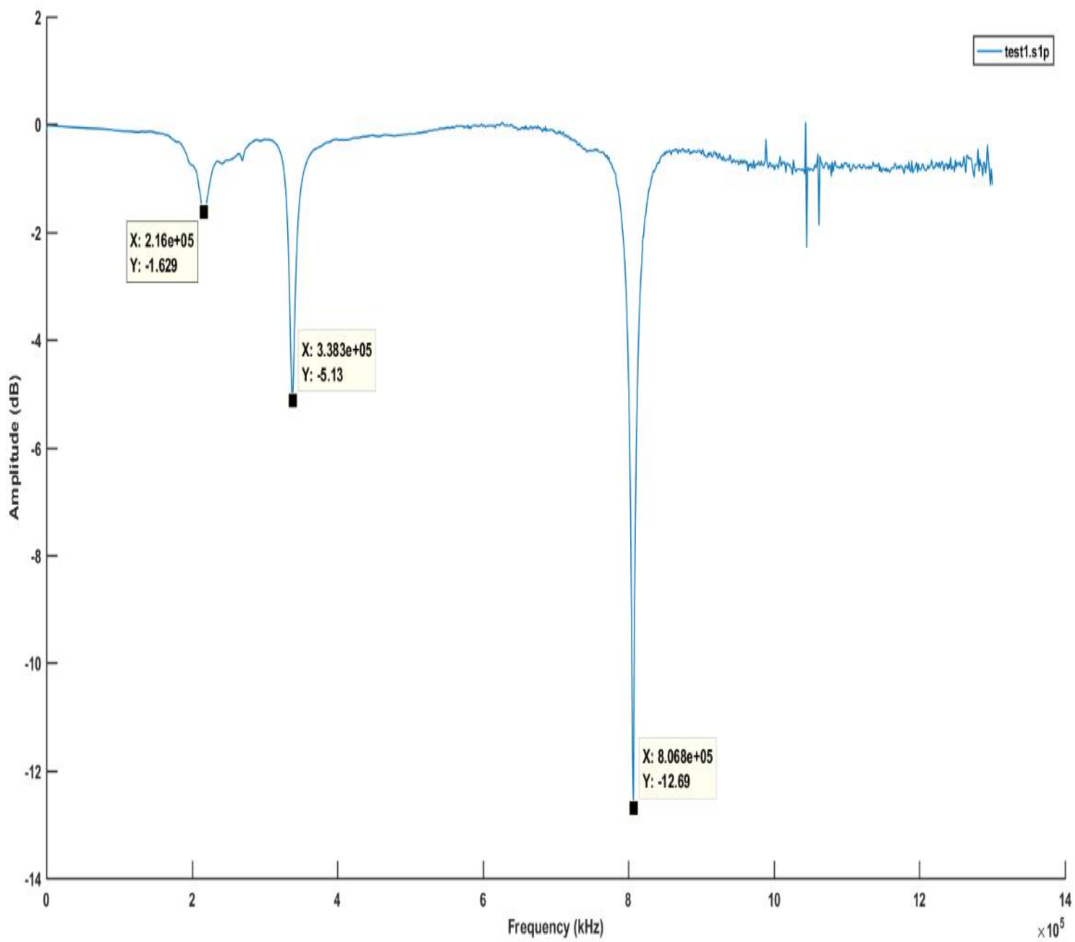


Figure 3.18: Illustrate the resonance frequency for a large square sensor was placed below the 1000 mL empty chamber. The resonance frequencies are 2.2 MHz, 3.4 MHz, 8.1 MHz respectively.

After that, the large skin patch resonators square and triangle were tested to characterize the outcome with and without removing the sensors and placed back again below the beaker. Repeatability is corresponded to steady placements sensor and reproducibility corresponded to change placement sensor. The result shows that when removing the sensor and placed back again the measurements would change. However, when the sensor has not been removed and takes the measurements at the same condition and position as the sensor, it would perform the same measurements by showing the linear correlation between the fluid volume changes and the resonance frequency.

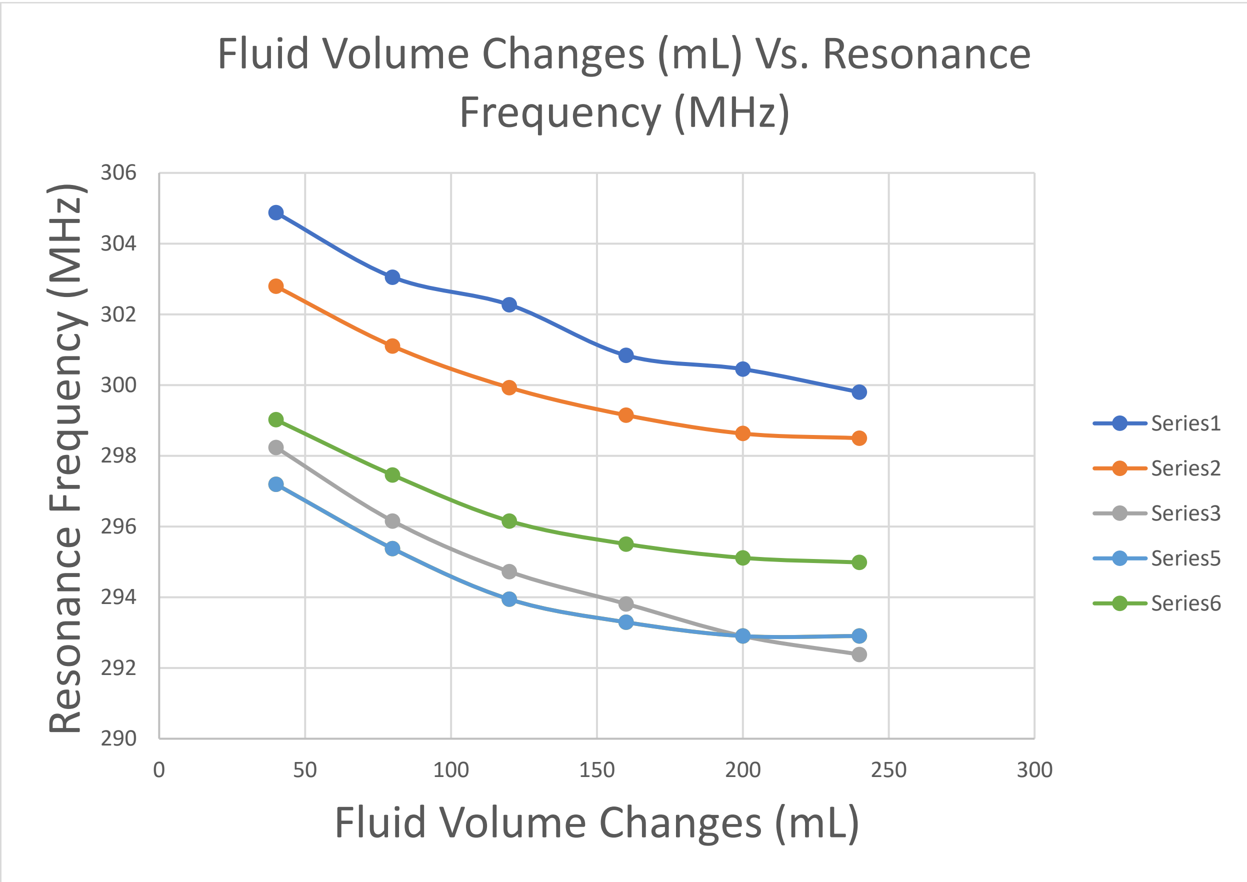


Figure 3.19: Illustrate the resonance frequency for a large square sensor was placed below the 250 mL size of the beaker without removing the sensor and changing the position.

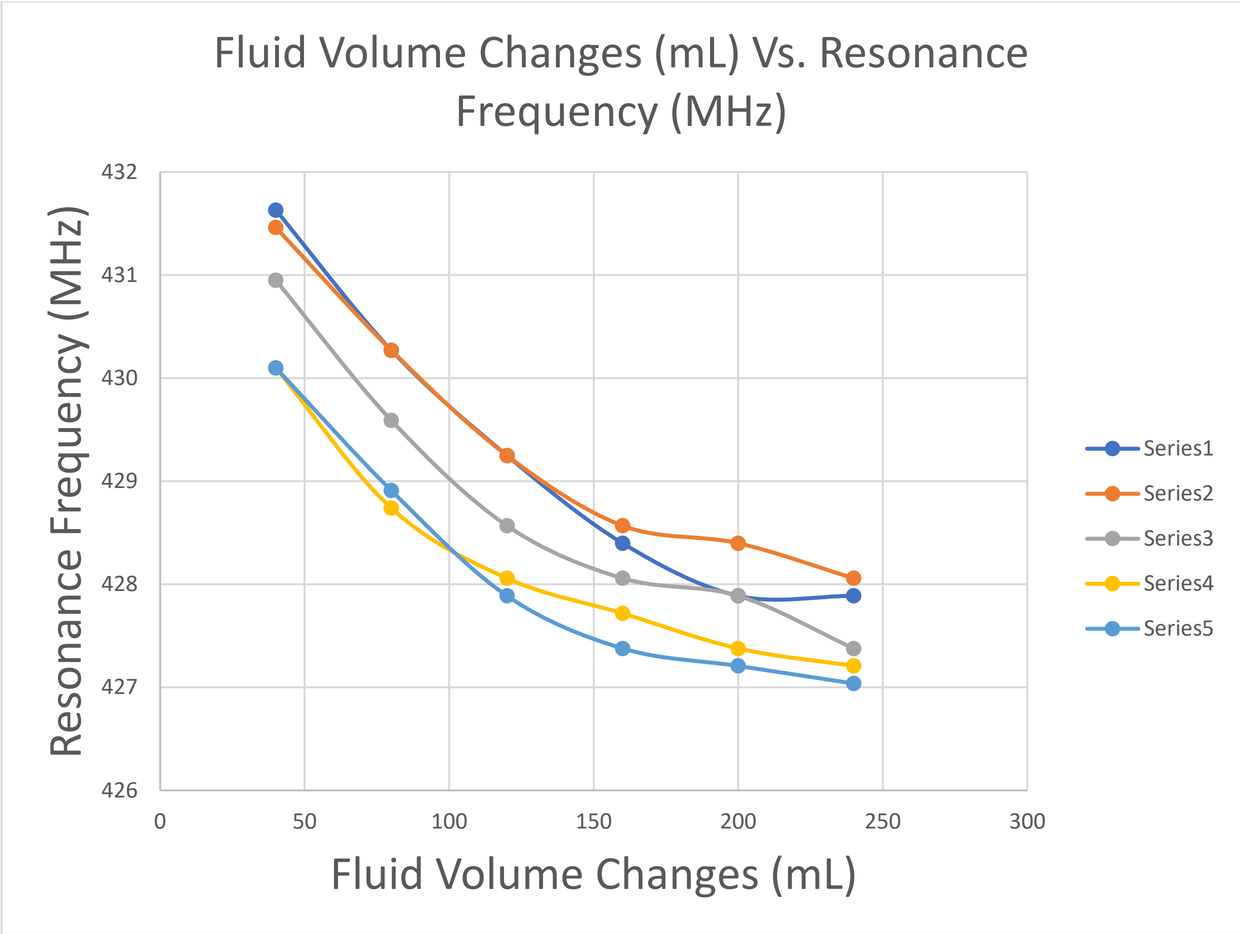


Figure 3.20: Illustrate the resonance frequency for a large triangle sensor was placed below the 250 mL size of the beaker without removing the sensor and changing the position.

3.3.5 Reproducibility:

The capability to achieve the same outcome while measuring the same quantity under various circumstances is known as reproducibility (i.e., time, observer, operating conditions, etc.). With respect to the resonant frequency, reproducibility is significant since the resonance frequency is important to be constant on each measurement while collecting the data (Kasahara et al., 2017).

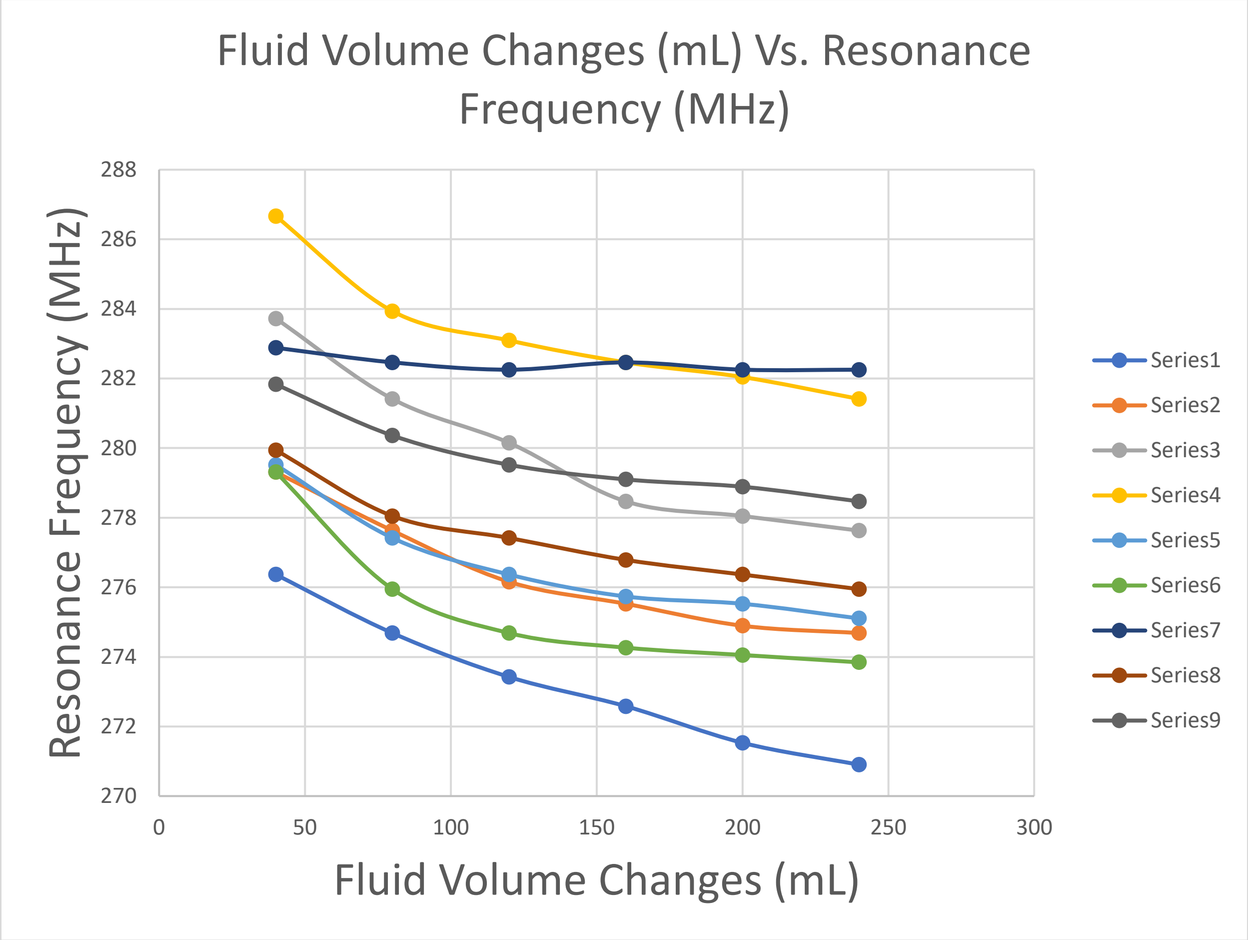


Figure 3.21: Illustrate the resonance frequency for a large square sensor was placed below the 250 mL size of the beaker by removing the sensor and placed back again.

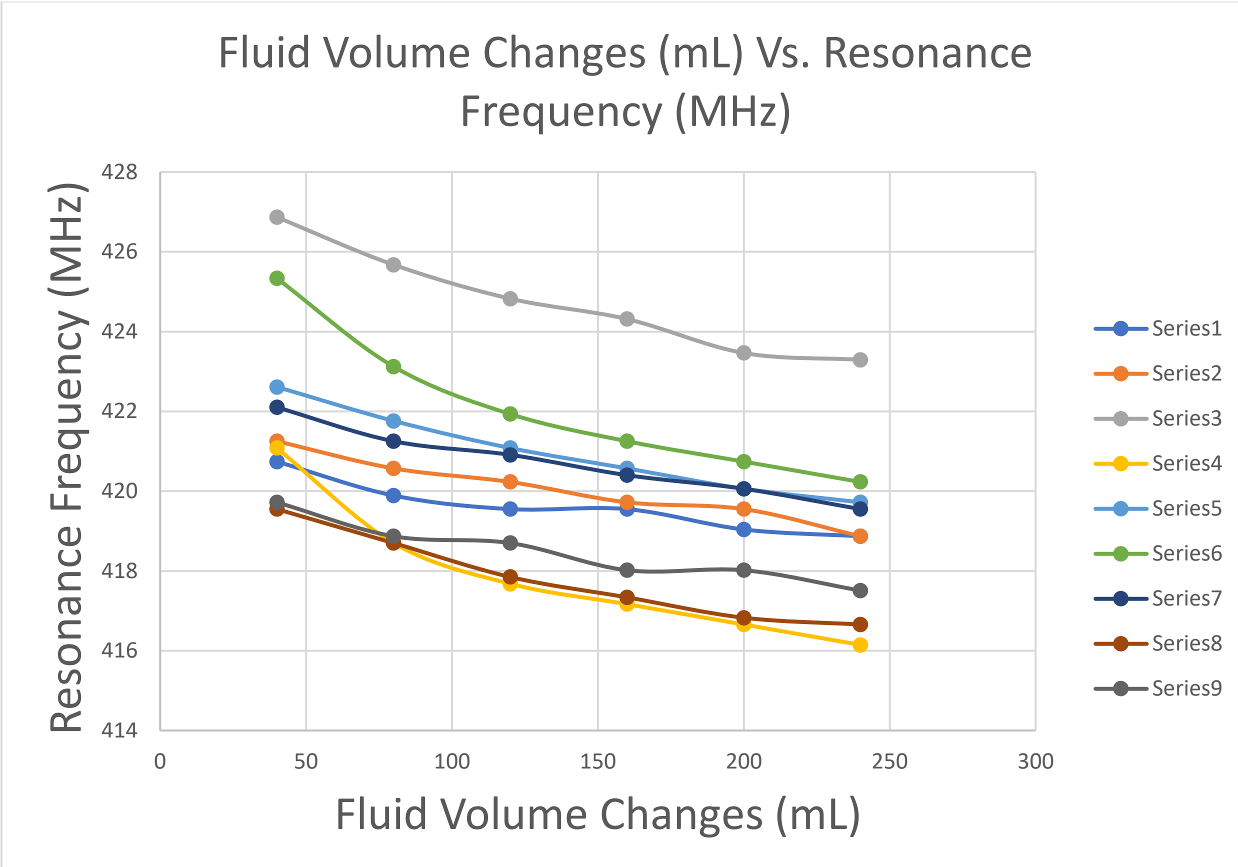


Figure 3.22: Illustrate the resonance frequency for the large triangle sensor was placed below the 250 mL size of the beaker by removing the sensor and placed back again.

3.3.6 Hysteresis:

Furthermore, other experiment has done to study the hysteresis of the sensor. The large square skin patch resonator was placed below 250 mL size of the beaker with increments of 40 mL. Moreover, started increasing the fluid from 40 to 240 mL and then decreasing the fluid volume from 240 until 40 mL. After that, the increments from 40 to 240 mL were used by random selection to characterize if the sensor would perform same result for resonance frequency.

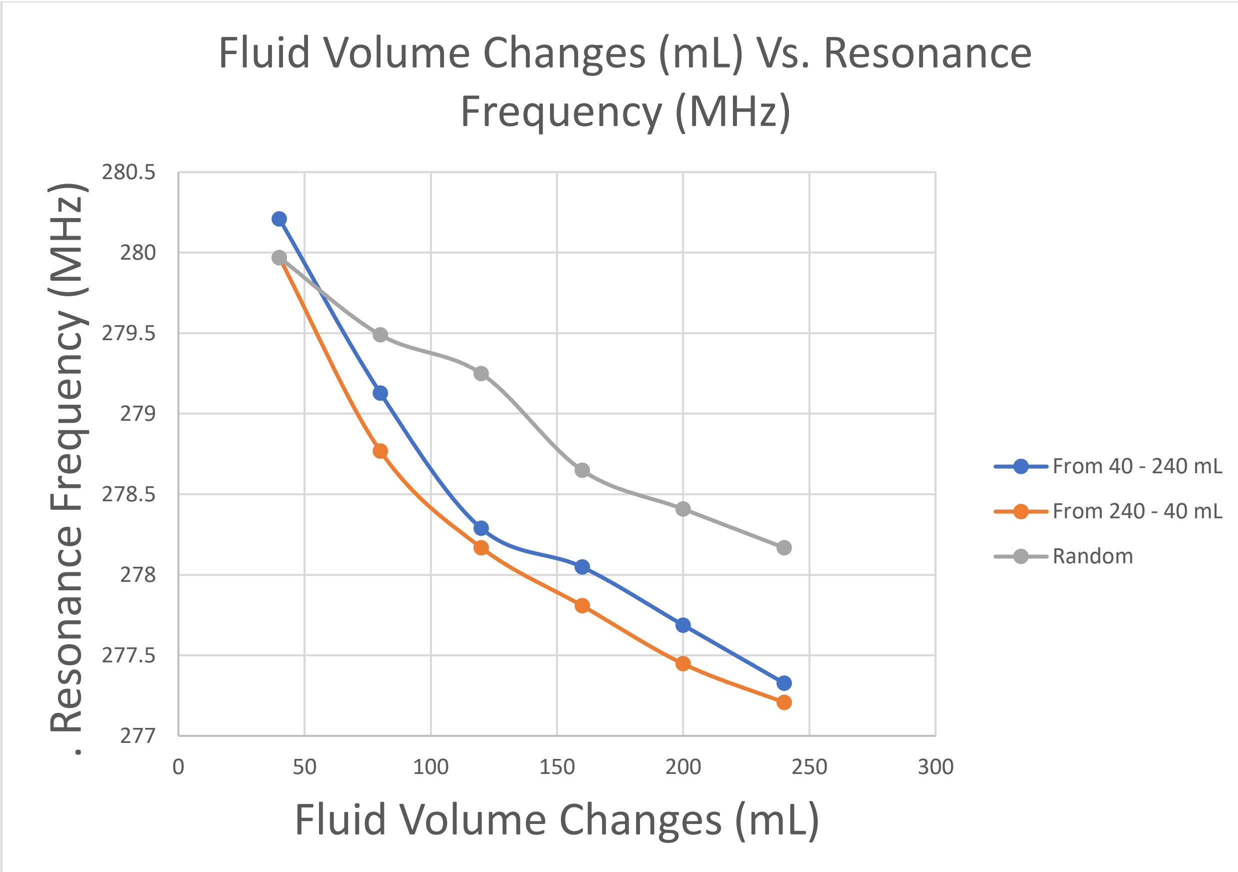


Figure 3.23: Illustrate the resonance frequency for the large square sensor was placed below the 250 mL size of the beaker by filling and aspirate the fluid volume.

The result indicate that the sensor can measure same resonance frequency in decreasing or increasing the fluid volume measurements in same position of the sensor. Moreover, the random selection measurements of fluid volume have slightly changed.

3.4 Discussion

In this research, the sensitivity and dynamic range were successfully determined by characterizing the sensor's performance with different sensor parameters. This gives us a view of point about the accuracy of monitoring the resonance frequency and demonstrates the correlation between the resonance frequency and fluid volume changes based on different sensors. The sensor design is critical and affects the sensor performance by changing the parameters of the sensor such as gap width, trace width, number of turns, and size of the sensor (Szatkowski, 2014). As the result illustrated, the larger size would have higher self-inductance due to the number of turns and the length of the trace. Furthermore, decreasing the gap width would demonstrate higher sensitivity due to the increases in the speed of the current (Stanley, 2014). The gap width for the sensors was adjusted to be 0.20 mm due to the limitation of the printer that could not print less than 0.20 mm. The shapes of the skin patch resonators illustrate that there are differences in data measurements despite overall parameters being constant. With the different sensor shapes, we want to ensure which sensor has accurate measurement data to enhance health monitoring of the organ's functionality inside the body related to fluid volume changes (YokoGawa, 2018). The result demonstrates that the large square spiral shape has higher sensitivity and dynamic range.

3.4.1 The Performance of the Sensor

The result demonstrates the sensor performance for fluid volume measurements specifically in dynamic range and sensitivity. The sensitivity was investigated by using different shapes and sizes of the sensor. We can conclude that the sensitivity would affect by changing the parameters of the skin patch resonator such as trace, gap width, and the number of turns. The large shapes of the four main designs had higher sensitivity than the medium and small due to bigger trace widths. Also, the large square and triangles have higher sensitivity than the large circles, and pentagons because the shape of the sensors plays an important role in how the electromagnetic wave is produced from the sensor.

Moreover, the repeatability was done by testing the sensor with and without removing the sensor to ensure the repeatability of the data collection. The large square and triangle shapes were tested in the 250 mL empty beaker to characterize the repeatability. Moreover, the flexible sensor is highly sensitive and causes different changes in reading when removed and placed back again due to how the sensor is bending or shaped and changing position each time. The flexible design was used to be suitable for the inclinations of the body. Furthermore, since the large square had accurate sensitivity and dynamic range, the sensor was tested in different beaker sizes to study the resonant frequency response. The result shows that the resonant frequency does not change no matter what the size of the beaker is. Also, since we are using a large scale for resonance frequency in (MHz), the slight changes in the resonant frequency would not affect the result and we will consider them as they are starting at the same signals. Additionally, the phase shift would characterize the oscillator performance for the sensor and determine the frequency and stability of the sensor. The figures 3.11, 3.12, 3.13, 3.14 shows that in each resonance frequency peak the phase shift turned to 90 degrees due to the RLC circuit which causes differences between the phase of the output voltage and the input voltage, and we can indicate the dynamic range (Thai Hsu, 2018). Lastly, the hysteresis is described as lagging in the electromagnetic wave. The concept of hysteresis is distinguished, generally, by the system’s divergent response to opposing inputs. The beaker was filling from 40 mL to 240 mL and after that aspirate the fluid by using the syringe in order to study the resonance frequency responds. The result indicates that filling and aspirate the fluid in the same amount of mL would have the same resonance frequency, which concludes that the sensor has hysteresis (The Electric Academy,2019).

3.4.2 Limitations and Future Works

Despite the correlation between the resonance frequency and fluid volume changes, this study has several limitations. The sensor design is playing an important role in this study to determine the sensitivity and dynamic range. The accuracy of the parameters for the sensors could be varied, such as gap width, trace width, and size of the sensor due to human mistakes. Also, the printer cannot print a size less than 0.20 mm, which is why we chose the gap width to be 0.20 mm. If we can print less than 0.20 mm, we would have better sensitivity for the sensors. Moreover, the increments of water would slightly make different changes in fluid level in each study and affect the outcome for the resonance frequency. Finally, the study was done by using a vector network analyzer that ranges between 1 kHz – 1.3 GHz whether there are other VNA varies between 9 kHz – 3 GHz would give a bigger picture and has high performance to study the resonant frequency. On the other hand, the future work of this research would test and repeat all the experiments on biological tissue since this study only focused on beaker study. Furthermore, study other shapes of RF resonators such as complex shapes, inverted F (PIFA), close circuits, and NFC tags, to compare the results with the current sensor designs.

3.5 Conclusion

In summary, wearable technology has gained huge interest in the medical field due to the wearable form factor and minimal required training for uses. Moreover, wearable technology would help to have early notice regarding health problems by monitoring the functionality of the organs in the body constantly. This research presents a comparison of skin patch resonators that may be useful to study the correlation between fluid volume changes and resonance frequency with different sensor design parameters. The objective of this study is to characterize the performance of the skin patch resonator specifically in sensitivity, repeatability, and dynamic range. The results indicate that the large skin patch resonator would have the best performance for measuring the fluid volume changes due to have long trace width and small gap width. Moreover, the large square skin patch resonator performed better than a large circle, triangle, or pentagon, which led to a view of the point using the square shape. Moreover, the future work of this study is to build a benchtop model and repeat the experiments to study the performance of the sensors. Furthermore, manufacture other sensor designs such as inverted F, NFC tag, and close circuit to characterize the sensitivity and dynamic range.

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