International Journal of Engineering Research And Management (IJERM)
ISSN: 2349- 2058, Volume-11, Issue-04, April 2024

Continuous Pressure Monitoring Sensor Based on RLC Circuit

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***Abstract*—Today, the increased utility and ease of use of electronic devices has facilitated people's lives. Smart sensors play a vital role in various fields such as digital analytics, agriculture, structural health monitoring and healthcare. Smart sensors embedded in wearable devices can collect large amounts of data in real time, allowing unobtrusive monitoring of people's lives. Wireless smart sensors and networking technologies offer more efficient and cost-effective solutions. With a variety of applications, they offer great potential for data collection, monitoring and analysis in various fields. Among them, pressure sensors are widely used in various industries to monitor and supervise pressure levels in different applications. Pressure sensors are cost-effective, provide precise pressure measurement, have a wide measuring range and stability, and are simple in construction, allowing flexible design and adjustment of the pressure detection range. Pressure sensors with a wide range of applications have a profound impact on society. Based on this paper, a capacitive pressure sensor is designed and developed.In order to achieve the measurement of pressure, this paper proposes to design a capacitive intraocular pressure sensor, which consists of a capacitor with parallel poles and a coil connected and coupled to form a sensor loop, which reads the change in frequency with the change in intraocular pressure through the reading coil. The change can be read through the coupling and has many advantages such as low cost, stability and high sensitivity. The design has a wide range of applications and is socially and medically important.**

***Index Terms*— RLC resonant, inductor coils,capacitor pole plate**

I. Introduction

Nowadays, the increased utility of electronic devices has facilitated people's lives, making them more dependent and in higher demand for healthy medical and highly sophisticated monitoring devices. The fast-paced life has also led to the need for certain monitoring of our physical needs as well. The various sensory organs of human beings are regarded as the medium through which we receive extraneous signals for transmission to the brain. People use their senses to gather information that is transmitted to the central system, and with the advancement of technology has allowed us to manufacture sensors to meet our needs and thus receive better information for us.

Sensors, as one of the convenient devices for receiving and monitoring, can convert the signals received and detected in a certain way into electrical signals or output them in other forms to meet the standard requirements. In order to meet the diversified functions, various types of sensors have been designed to obtain different information with different functions. Sensors can detect pressure, temperature, and moderately used in a wide range of applications such as tactile sensing[1], fingerprint recognition[2], and so on.

Pressure sensors are widely used in various industries and applications. They play a vital role in measuring and monitoring pressure levels. Advances in technology have led to the development of different types of pressure sensors with higher performance and compact size. One area of research focuses on the use of polymer composites, particularly conductive polymers, in flexible pressure sensing applications. These sensors exhibit higher sensitivity, durability and response time when used in combination with conductive polymers[3]. Simplifying the design and manufacturing process, they can perform a wide range of pressure measurements and find applications in aerospace, automotive and biomedical fields . In addition, pressure sensing devices can be designed with deformable and non-deformable diaphragms, force transfer devices, and detection electrodes to accurately measure external forces. As an important component of sensors, pressure sensors can detect signals from physical signals such as pressure vibrations and can be converted into electrical signals that can be processed for acceptance[4]. Pressure sensors can lead to new interaction scenarios and hence are more developed to adapt to complex changing environments and can withstand some degree of deformation. Pressure sensors have long term significance for health monitoring, modern wearable devices with high demand for wireless power and communication, and the development of pressure monitoring. Pressure sensors can be categorised based on their design and function. One approach is to use capacitive pressure sensors as an alternative to force sensing resistors (FSR) for gait analysis [5]. Another approach is to use a pressure sensing device that consists of deformable and non-deformable diaphragms, where one diaphragm has a pressure-sensitive material and the other diaphragm has a detection electrode. Furthermore, the pressure sensor may comprise a transparent substrate layer, an electrode layer, a light emitting layer and an electrification layer, the electrode layer comprising insulated first and second electrodes arranged in a crosswise manner [6]. Another classification is based on the use of particles that are deformable under pressure, which causes a change in resistivity and allows the measurement of pressure. These different types of pressure force sensors have various advantages and can be used for different applications.

There is an ongoing quest for a more effective and convenient detection mechanism, and pressure sensors can be used to better monitor pressure, which comes from external stimuli. Pressure can come in a variety of forms, including pressure on internal organs, pressure from outside the body,

Manuscript received April 22, 2024
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such as fluid pressure in the case of knee problems, pressure on the soles of the feet when sitting or standing, and intraocular pressure in the case of glaucoma.

Glaucoma is one of the three leading causes of blindness in the human eye, and is also the second most common blinding eye disease in China. As the number one blinding irreversible eye disease in the world, glaucoma is damaging the visual health of tens of millions of people worldwide. Tens of millions of people worldwide suffer from a serious disease of the optic nerve. A prevalence of up to 3.5 per cent occurs between the ages of 40 and 80. It is expected that by 2040, there will be 180 million people with glaucoma worldwide [7]. An important indicator for the diagnosis and treatment of glaucoma is intraocular pressure. Studies have shown that by observing the fluctuation curves of IOP in normal people and patients with glaucoma, it is well established that more than half of glaucoma patients have IOP problems at night, but most of the patients with IOP seek medical attention during the daytime, so they are not able to accurately assess their glaucoma condition, which in turn affects the timely detection and diagnosis of glaucoma. IOP varies with location, time of day, corneal thickness and sleep quality. Measurement of IOP can be widely used as an important physiological indicator in the diagnosis and evaluation of glaucoma[8], and can be used by clinicians as an indicator for reference, based on the demand for monitoring pressure in all aspects of people's lives as mentioned above, the measurement of pressure is quite important，the schematic diagram is shown in Figure 1.

In summary, the convenience and real-time for the purpose of better monitoring the pressure. Through the design of a capacitive pressure sensor system, timely and convenient access to pressure fluctuations, and then can be an early understanding of the changes brought about by the body pressure, the possible problems brought about by the situation, the development of subsequent methods and monitoring is very important, is very meaningful.

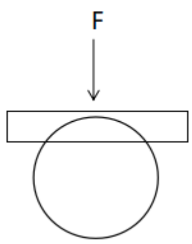

Figure 1 Schematic diagram of flattening

II. Working Principle

There are many functions of smart sensors, including the ability to detect temperature, pressure and tension by being its main function. A wearable physical sensor was developed that is flexible and stretchable enough to withstand deformations caused by human activities [9,10]. Flexible electronics is a technology that allows electronic devices to be mounted on flexible plastic substrates. These devices are usually mounted on materials such as polyvinyl alcohol, polyamide and polyester. They are lightweight, can change shape and function, and fit tightly. The concept of flexible electronics, a concept that has been around for decades. Amorphous silicon in the following decades meant that great strides were made in flexibility and processability, and as a result, these materials became the basis for electronic devices that require bending, rolling, folding and stretching, as well as other characteristics that conventional electronics cannot fulfil. In recent years, flexible electronics have been used in areas such as artificial intelligence, the Internet of Things, and medicine and health, and have brought about changes in related fields[11].

This project focuses on the framework of creating a sensing system using RF line sensing technology and RLC circuits, explaining the principles of electromagnetic coupling and using HFSS software to analyse and simulate the antenna parameters, experimentally determining and verifying the antenna parameters, describing the role of the RLC resonant circuits [12] and describing the process of circuit development. After preparing the circuit equipment, the sensor was connected to an oscilloscope in order to determine the optimum operating distance based on voltage readings. The pressure sensor is low cost, highly sensitive and can accurately sense pressure changes even without an external power source. The sensor has high mechanical reversibility, durability and stability, making it suitable for a variety of applications, especially in the medical field.

Our sensor is a passive electromagnetic sensor design based on passive electromagnetic telemetry technology, which does not require an internal power supply like active sensors with internal active sensors. The sensor unit operates through an RLC resonator circuit (Figure 2) consisting of a capacitor (C), an inductor (L) and a resistor (R). Changes in any one or two of these three elements can be detected by reading changes in the resonant frequency of the resonant cavity. When deformed under different pressure conditions, the inductance of our device remains constant, the capacitance changes significantly, and the passive change is negligible. Under conditions of varying external pressure, the capacitance changes significantly and the spacing of the electrode plates between the capacitors is deformed, resulting in a change in capacitance and a negligible change in resistance. This results in a change in frequency as shown in the following equation:

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{C_S L_S}} \tag{1}$$

Sensors due to the pressure capacitance of the need for capacitors and coils to achieve the realization of the sensor part of this part of the principle to design the appropriate parameters of the coil and capacitance, based on the RLC circuit, the circuit diagram on the left side is a signal source with the equivalent circuit diagram of the transmitting coil, the transmitting coil equivalent to the inductance L1 in series with the resistor and then in parallel with capacitance Ca1, the equivalent circuit diagram on the right side of the receiving coil connected to capacitance sensors Ca2, the receiving coil equivalent to inductance L2 and resistance and Ca3 parallel. The receiving coil is equivalent to an inductor L2 connected in series with a resistor and Ca3 connected in parallel. The other part can be divided into the reading coil and induction between the small coil, based on the principle of electromagnetic coupling, the reading coil is connected to one end of the signal generator, signal generator is also known as signal element or oscillator. The signal generator is used for the specific parameters required by the circuit under test electrical test signals, the basis and core of the frequency generation, the output of the changing frequency, different AC signal output voltage output to the reading coil. The coupling of the two coils reads the change in frequency and voltage, and the reading of voltage and frequency data is carried out without the use of pressure.

A typical capacitive sensor is an ideal parallel plate capacitive structure consisting of two parallel metal plates separated by a dielectric (insulating substance). When a certain pressure is applied, the distance d between the two plates and the area S of the two plates facing each other will change, thus causing a change in capacitance, as shown in the schematic diagram in Figure 2. When the pressure inside the eye changes, the capacitance of the pressure sensor changes, and the voltage and frequency of the whole circuit changes.

$$C_0 = \frac{A \times \varepsilon_r \times \varepsilon_0}{d} \quad (2)$$

where C is the capacitance value, the relative dielectric constant of the dielectric material between the plates; is the absolute dielectric constant; d is the distance between the two parallel plate electrodes and A is the relative area between the parallel plates.In the high-frequency mode, the coil can be equivalent to an inductor due to the presence of the skin effect, and for the loop antenna, the equivalent inductance is given by the following equation:

$$L = 2 \times l \times [\ln(\frac{l}{D}) - k] \times N^{1.8} \quad (3)$$

where l is the length of the outermost turn of the coil in cm; D is the width of the coil wire in cm; K is the shape factor; N is the number of turns of the coil. D is the width of the coil wire in cm; K is the shape factor; N is the number of turns of the coil. The equivalent inductance of the coil can be calculated by the above formula, and the inductance values at different frequencies can also be calculated by simulation. The results of the formula and simulation are compared with each other and are accurate within the error range.

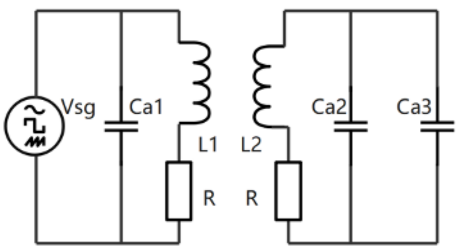

Figure 2 Equivalent Circuit Diagram of Pressure Monitoring System

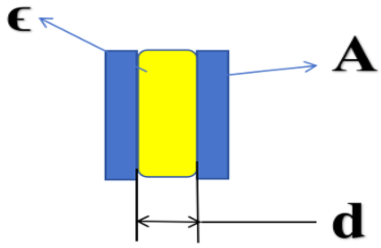

Figure 3 Capacitive Sensor Principle Schematic

The effect of the resistance can be neglected when the parasitic resistance is low. The following equation shows the overall resistance (R) across the serpentine wire:

$$R = \rho \frac{l}{A} \quad (4)$$

where ρ is the electrical resistivity of the material, l is the length of the wire, and A is the area of the crosssection of the wire.

III. Sensor Materials

Magnetic permeability is the ability of a material to conduct magnetic flux. It is an important property for a variety of applications, including heat transfer devices and structural health monitoring of ferromagnetic materials. The concepts of paramagnetic and antimagnetic substances are explained in terms of their permeability (μr) values. substances with μr > 1 are known as paramagnetic substances, e.g. ferromagnetic substances such as silicon steel sheets and cast iron. Paramagnetic substances produce a weak magnetic field in the same direction as the external magnetic field, thus increasing their strength μr<1 are called antimagnetic substances, such as copper and lead. Antimagnetic substances produce a weak magnetic field in the opposite direction to the external magnetic field, thus weakening the total magnetic field, which is expressed as the antimagnetic effect. Copper is an antimagnetic material with good electrical conductivity and a low price, and its relative permeability is close to 1, making it ideal[13].Therefore, the material chosen for the coil and the capacitor plate is copper.

By analyzing the working principle of the capacitive pressure sensor, a flexible material with a small Young's modulus should be selected as the dielectric layer. dielectric layer, so medical silicone (AZoMaterials) was used as the sensor dielectric layer. In the previous test phase, insulating gel was used as the dielectric. Medical silicone as a dielectric material has a series of excellent characteristics such as temperature resistance, oxidation, hydrophobicity, flexibility, permeability, aging resistance, high transparency, physiological inertness, non-adhesion to human tissues and blood, good bio-adaptability, non-toxicity, tastelessness, non-carcinogenic and so on[14], and its relative permittivity is 2.9, Young's modulus is 1×10^6 Pa.

IV. Sensor Design And Fabrication

The size of the inductor coil is selected through experimental simulation, including parameters such as the radius of the coil, the distance between the inner diameters, and the number of turns.As the number of turns changes, the size of the series resistance and parasitic capacitance changes accordingly. When the parameters such as the inner diameter are certain, the Q value in the low frequency band does not change much as the number of turns keeps increasing, however, the Q value in the high frequency band peaks and then gradually decreases[15]. Experimentally the number of turns keeps increasing from 3 turns to 4 turns and then 5 turns and as the number of turns increases the resonant frequency of the RLC resonant circuit decreases. Similarly in order to verify the correctness the distance between the coils is also set for the overall effect. The spacing between the coils is varied with fixed parameters to verify the different effects of spacing between coils with different wires. It is determined that the radius of the copper wire coil is 0.25mm, the inner diameter of the coil is 10mm, and the number of turns of the coil is 3 turns to vary the distance between the different coils. The coil distances can be 0.1mm, 0.5mm, and 1mm. experimentally to verify, the effect of spacing between coils.

The verification of coil parameter selection using oscilloscope reading, in the case of changing one parameter, change the other parameters for verification as shown in the table.

Table1 experimental control chart

	Distance	Coil radius	Coil inner diameter	Coil distance	Frequency
Turns N=3	0.5cm	0.25mm	10mm	0.1mm	24.85MHz
Turns N=4	0.5cm	0.25mm	10mm	0.1mm	10Mhz
Turns N=5	0.5cm	0.25mm	10mm	0.1mm	8.654MHz

Therefore, according to the above experimental analysis, it is verified that the inductive coil is related to many parameters, such as the inner diameter of the coil, the number of turns of the coil, and so on. These parameters are merely interconnected, and the adjustment of the relevant parameters should also be carried out according to the actual in the preparation. The diameter of the pupil of the human eye is about 5mm in the case of light. Therefore, in this paper, the diameter of the coil is fixed at 8mm, the number of turns of the coil is 6 turns, and the spacing between the coils is 0.1mm, which is used to ensure the normal visual line of the wearer.

Copper is an antimagnetic material with good electrical conductivity and low price, its mechanical properties of the stretching softness is better, so you can choose the purple copper sheet as the capacitance sensor on both sides of the pole plate electrode. The sensor electrode selected for this experiment is a square electrode, square electrode is easier and more convenient to prepare, select the side length of 4mm as the electrode, the electrode plate thickness of 2mm and 3mm. the electrode pole plate thickness of the different to verify whether the thickness of the signal frequency impact. In the case of other parameters must be, the first choice of thickness of 0.2mm of copper violet sheet, selected the parameter performance of better medical silica gel as a dielectric, the two electrode plate and coil welding, complete the preparation for the experiment.

V. Experiments And Results

This paper presents a passive wireless capacitive sensor that responds to pressure. The capacitive pole plates are deformed under pressure and the distance between the plates changes between the capacitors. The induction coil is an induction antenna used for reading data. The induction antenna is used for wireless data reading. This method of reading wireless data relying on near-field electromagnetic coupling has a loop antenna form that does not interfere with normal vision, and its form expands the coil's ductility and improves sensitivity to corresponding changes.

In order to simulate pressure, this can be done by using solid state pressurisation simulation using weights of different weights and the reading coil measures the voltage and frequency response in the circuit through an oscilloscope. The inductor coil is made of copper wire with a spacing of 0.1mm per turn as shown in Fig. 4 with an inner diameter of 10mm and 6 turns. The size of the capacitor plate is 4mm, the thickness between plates is 0.2mm and the dielectric is medical silicone.

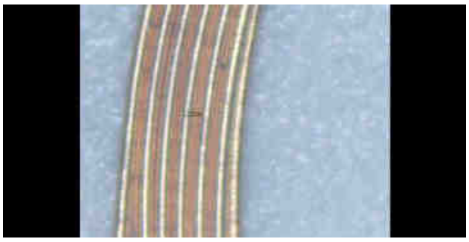

Figure 4 Schematic of an inductive coil under a microscope

Silicone rubber is a very good performance of polymer medical material, used as a medical artificial material, it is relatively low cost, practicality, not prone to rejection, does not have any harm to the human body, biological adaptability is good, not with the human body's capillaries pasted up.Spin-coating the prepared liquid medical silica gel on the capacitor plate as a dielectric.

The effect of the plane angle between the sensor coils on the sensing performance was tested at different angles, 0, 45degrees and 60 degrees, and the results are shown in Figure 5. The data shows that the angular deviation does not cause any shift in the resonant frequency of the sensor. The shift in the resonance frequency of the sensor can still be detected at extreme angles. The signal is still detected at an extreme angle of 60 degrees.

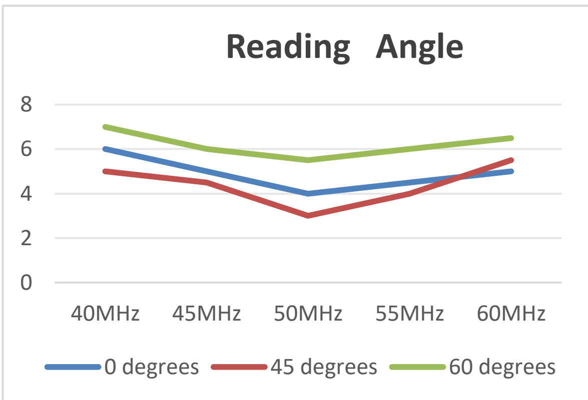

Figure 5 Frequency responses of the sensor at different planar angles

It is important to note the limitations of our current testing results.For other tests, the difference in distance between the reading coil and the sensor coil was tested, and the effect on the signal at different distances was tested separately. Two alligator clips of the oscilloscope were added to the coil and the difference in voltage was observed by varying the distance. Four sets of h distances were selected and the readings were observed, marking the maximum and minimum values as shown in Table 1.

Table1 Data for different distances h

h(cm)	max(V)	min(V)	max-min(V)
0.5	1.975	-2.025	4
1	0.79	-0.81	1.6
2	0.395	-0.405	0.8
3	0.02475	-0.2025	0.227

The table above visualizes that the amplitude of the voltage waveform is decreasing as the distance h between the voltage capacitance coil and the emission source reading coil is increasing. At the optimum distance, the voltage amplitude obtained at h of 0.5cm is the largest and the received signal is the strongest. Therefore at h of 0.5cm the received signal strength is maximum and so more energy can be supplied to the circuit.

By analyzing the working principle of the capacitive pressure sensor, combining the performance of the device and material processing, pressure testing, circuit detection conditions and other factors, this paper designs the electrode of the sensor as a square structure with a side length of 4 mm and a thickness of 2 mm.Through the thickness of the dielectric layer, the area of the pole plate of the side length, according to equation(2) and the following pressure sensitivity equation:

$$S_P = -\frac{C_0}{E} \tag{2}$$

From the above theoretical calculations of pressure sensor sensitivity, it can be seen that: capacitive pressure sensors based on silica gel film are more sensitive than most of the current cavity sensors, and silica gel is more suitable for use as a dielectric layer material than polyimide and polyethylene, for example. Silicone is more suitable as a dielectric layer material than polyimide. After systematic testing of the response of capacitive micro-pressure sensors with silica gel as the dielectric layer to applied pressure at room temperature of 25 °C, a good sensitivity of this set of capacitors to applied pressure was measured. The maximum value of the pressure applied to the sensors by means of weights during the pressure increase was 6.1 kPa and the minimum was 0.3 kPa.

After a defined distance h, the working distance behind will remain constant. The sensor was tested in repeated cycles under pressure and the repeated tests did not affect the resonance frequency of the sensor, proving the stability of the sensor in a given situation. The test results under different pressures applied from outside are shown in Fig. 6.

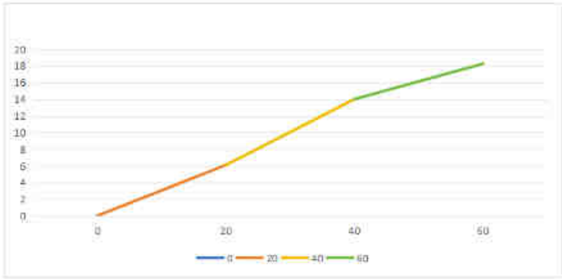

Figure 6 represents the pressure change versus frequency change

VI. Discussion And Conclusion

This report presents a wireless passive capacitive pressure sensor. The sensor consists of a coil and a bipolar plate capacitor. The capacitor is made of soft copper sheets sandwiched in medical silicone for better biocompatibility. Pressure is applied to the upper plate of the capacitor at room temperature of 25 degrees Celsius using weights to simulate solid state pressure application. As the pressure increases, it pushes the upper plate downwards, thus decreasing the distance between the two plates, with a consequent increase in capacitance value and a consequent decrease in frequency. The frequency response of the sensor was measured and the antenna was connected to an oscilloscope (DSOX3054A, Keysight InfiniiVison 3000X) to measure the corresponding frequency of the sensor as well as the voltage profile. The higher the pressure, the heavier the pressure sensing and the smaller the radius of curvature, resulting in a larger output voltage signal; the lower the pressure, the smaller the output voltage signal. Conversely, the higher the pressure, the lower the output frequency.

By analyzing the current state of research, we propose a capacitive pressure sensor, and through modeling, simulation and process optimization and figuring out, we fabricated a capacitive pressure sensor with excellent performance, and realized high sensitivity pressure detection by building a test system.

The fabrication process and method of the micro-nano structure of this sensor are investigated, and compared with the capacitive pressure sensor with cavity structure, this capacitive micro-pressure sensor has a simple process and higher pressure sensitivity. The research work in this paper The research work in this paper provides a new idea for the research of flexible microcapacitive sensors.

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