Design of A Linear Variable Differential Capacitive Angular Transducer (LVDCAT) for Automobile Brake System

A Thesis

Submitted By

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THESIS CERTIFICATE

This is to certify that the thesis titled **"Design of A Linear variable Differential Capacitive Angular Transducer (LVDCAT) for Automobile Brake System ",** submitted by **Mr. Habeeb Rahman K,** to the Indian Institute of Technology Madras, Chennai for the award of the degree of **Master of Technology,** is a bona fide record of research work done by him under my supervision. The contents of this thesis, in full or a part has not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

This thesis focuses on the design, fabrication and hardware testing of a Linear Variable Capacitive Angular transducer (LVDCAT) for automobile brake System. Conventional brake shoe wear out indicators do not indicate the amount of brake shoe wear out. LVDCAT can continuously monitor brake shoe wear out and can display amount of the brake shoe left on the brake pad. In the brake system as the brake shoes wear-out, a camshaft connected in the brake system makes an angular movement. The developed LVDCAT attached to this camshaft senses the amount of angular displacement (in degrees), where from the wear amount and the remaining life of brake shoes can be ascertained. The dimensions of the prototype are set such that it can be easily integrated in to the brake system.

The designed capacitive angle transducer provides a direct digital output which is linearly proportional to the angle being sensed. The range of angle for which testing is done is 0° to 180°. The variations in the sensor capacitances are converted to digital employing dual slope capacitance to digital conversion (DSCDC) principle. High accuracy is easily obtained since the output is dependent only on a dc reference voltage and a high frequency clock.

The prototype of the sensor is fabricated using three copper clad boards, a plastic case provided by the manufacture with the help of etchant (ferric chloride) and lathe machine. Hardware testing is done by building signal conditioning circuit on NI ELVIS board. ARDUINO UNO board is used for controlling the switches in the signal conditioning circuit and also for displaying the angle sensed. The LVDCAT has given nice linear variation in differential push-pull type of capacitances against the variation of Angle.

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ABBREVIATIONS

ADC	Analog-To-Digital Converter
AVR	Advanced Virtual RISC
CDC	Capacitance-To-Digital Converter
CLU	Control and Logic Unit
CMOS	Complementary Metal Oxide Semiconductor
DDC	Direct Digital Converter
DMM	Digital Multimeter
DSA	Dynamic Signal Analyzer
DSCDC	Dual-Slope CDC
EEPROM	Electrically Erasable Programmable Read-Only Memory
EMI	Electro-Magnetic Interference
FGEN	Function Generator
FR	Flame Resistant
ICSP	In Circuit Serial Programming
LVDCAT	Linear Variable Differential Capacitive Angular Transducer
NI	National Instruments
ELVIS	Educational Laboratory Virtual Instrumentation Suite
PCB	Printed Circuit Board
SPDT	Single-Pole Double-Throw
SRAM	Static random-access memory
USB	Universal Serial Bus
VPS	Variable Power Supply

CHAPTER 1 INTRODUCTION

1.1 TRANSDUCERS:

Electronic instrumentation system consists of an input device, a signal conditioning & processing device and an output device. These devices together are used to perform a measurement and record the result.

The input device receives the quantity that is to be measured and delivers a proportional electrical signal to the signal conditioning device. In the signal conditioning device, signal processing such as amplification, filtering or modification to a format acceptable to the output device are carried out. The output device may be a simple indicating meter, an oscilloscope, or a chart recorder for visual display. Depending upon what is to be measured and how the measurement result is to be presented type of these three devices are determined.

Measurable quantity for most of the instrumentation system is nonelectrical. These quantities must be converted to electrical in order to use electrical methods and techniques for measurement or control of these inputs. And this conversion is made by a device called "Transducers".

The sensor or the sensing element is the first element in a measuring system and takes information about the variable being measured and transforms it into a more suitable form to be measured. Sensor is sometimes called a primary measuring element, it can be found simply as a capacitive sensor or resistive sensor or inductive sensor depending on the application.

Sensors have to be embedded in the transducer to perform its intended function. Transducer consists of a primary element (sensor) plus a secondary element (signal conditioning circuit) that transforms physical variables to active signal such as changes in current or voltage. Figure 1.1 illustrates the difference between sensor and transducer

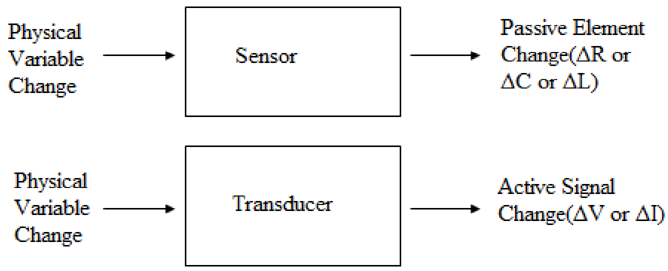

Figure 1.1: Principle of Sensor/Transducer.

Example: In Linearly Variable Differential Capacitive Angular Transducer (LVDCAT), the capacitance depends on the angular movement of the sensor. It can be inserted into a signal conditioning circuit (secondary element) in order to transform the change in the capacitance value to a change in the voltage output. Finally, the output voltage from the signal conditioning circuit express about the angular change value. In general, we can say that: **Transducer = Sensor + Signal conditioning circuit**

1.2 CAPACITIVE ANGLULAR SENSOR IN BRAKE SHOE WEAR INDICATION:

Angle sensors are required in many application areas like automobile, ship, aerospace and industrial automation. Most of the transducers for sensing an angle of rotation provide an analog voltage or current output. There are angle sensors based on the resistive potentiometer principle, Optics, magneto-resistive, Hall effect, capacitive angle sensors etc. capacitance-type sensors are widely employed in the industry for sensing displacement (linear and angular), pressure, and acceleration as they provide better resolution, sensitivity, and linearity compared with other types of sensors. LVDCAT is an angular sensor for automobile brake system based on capacitance transducer principle.

Typical brake pad wear sensors use a simple electrical contact to switch on a warning indicator. These warning devices only provides an indication that pad is totally worn out or not and it does not gives the amount of wear left on the brake pads as it. The designed brake pad life may be cut short due to premature brake pad replacement as there is an uncertainty in occurrence of failure of these brake pads. It is important to monitor the wear of the brake pad continuously so that failure of brake can be predicted accurately and premature removal of brake pad can be avoided. Thus service life of the brake pad can be increased than in the earlier case. LVDCAT can continuously monitor brake shoe wear out and can display amount of the brake shoe left out on the brake pad. Capacitive angle Transducer are simple in construction and provide low power, contact-less and maintenance free operation.

1.3 OBJECTIVE AND SCOPE OF THE WORK

The main objective of the work described in this thesis is to design a prototype of Linearly Variable Capacitive Angle Transducer (LVDCAT) which will sense the angular movement and display the angle on a display unit. This type of angle sensor finds application in automobile brake system to sense the life of brake shoes. As the brake shoes wear-out, a camshaft connected in the brake system makes an angular movement. If we connect the middle plate of our angle sensor to this camshaft, the angular movement of this camshaft can be sensed and hence wear out of brake shoe can be continuously monitored. Since the sensor is fabricated using copper clad board so it is an affordable sensor and also it has the advantages of a capacitive angle sensor over the other types of sensors as mentioned above.

1.4 ORGANIZATION OF WORK

A brief introduction to transducers and capacitive angular sensors is presented in Chapter1. Chapter 2 deals with design of the angle sensor and its fabrication technique. Chapter 3 explains the working of signal conditioning circuit used in the design of LVDCAT. Chapter 4 describes hardware set up used for the experiment. Chapter 5 provides experimental results of the designed LVDCAT. The conclusion of the work carried out and its future scope is provided in Chapter 6.

CHAPTER 2: SENSOR DESIGN AND FABRICATION

2.1 INTRODUCTION:

The proposed Linearly Variable differential Capacitive angle Transducer (LVDCAT) work on the principle of a capacitive traducer. The changes in capacitance of transducer can be measured easily and it is calibrated against the input quantity, thus the value of the input quantity can be measured directly. The advantages of capacitive sensors are that they consume very little power, their cross sensitivity to temperature is very low, no mechanical wear& tear and also shielding stray electric fields is less complex than shielding inductive sensors from magnetic disturbances. Capacitive sensor elements can be applied in many applications to measure many different types of signals such as displacement, proximity, humidity, acceleration, liquid level, gas concentration, etc. Capacitive sensors can be implemented on printed-circuit boards, glass substrates, silicon chips, or other types of material. Because the electrodes of a capacitive sensor element do not need to be in mechanical contact with each other, they are suited for small-range contact-less sensing. The main drawbacks of capacitive sensors concern their sensitivity to contamination & condensation, and their sensitivity to Electro-Magnetic Interference (EMI). There are different types of capacitive transducers

2.2 PARALLEL PLATE CAPACITIVE TRANSDUCER:

A parallel plate capacitor comprises of two parallel metal plates that are separated by a dielectric material. In the typical parallel plate capacitor the distance, Area and dielectric constant between the two plates is fixed.

The capacitance C between the two plates of capacitor is given by: $C = \frac{\varepsilon_o \, \varepsilon_r \, A}{D}$

Where C is the capacitance of the capacitor, ε_o is the absolute permittivity, ε_r is the relative permittivity, The product of ε_o & ε_r is also called as the dielectric constant of the capacitor, A is the area of the plates and D is the distance between the plates. A capacitance transducer can be made by varying any of these three parameters of a capacitor. It can be seen from the above formula that capacitance of the capacitive transducer can depend on the area of the plates, distance between the plates and the dielectric constant of the material used between the plates.

In the instruments using capacitance transducers, the value of the capacitance varies due to changes in any of these three parameters with the change in the value of the input quantity to be measured. This change in capacitance is sensed and it is calibrated against the input quantity to provide the required measurement.

Thus the capacitance of the variable capacitance transducer can change with the change of the dielectric material, change in the area of the plates and the distance between the plates. Depending on the parameter that changes for the capacitive transducers, they are of three types as mentioned below.

- **Changing dielectric constant type of capacitive transducers:**

Capacitance of the transducer changes with the variation of dielectric material between the two plates changes. The value of the dielectric constant changes with the variation of input quantity to be measured and the capacitance of the instrument changes accordingly. This capacitance, calibrated against the input quantity, directly gives the value of the quantity to be measured. This principle used in the Aircraft fuel level indication system. Here a Fuel probe is fitted inside the fuel tank and when there is no fuel air will be the die electric constant for calculation of fuel probe capacitance. As fuel level is increased dielectric constant of fuel will replace the air in calculation of Fuel probe capacitance and accordingly fuel level will be measured and indicated. Apart from level, this principle can also be used for measurement of humidity and moisture content of the air.

- **Changing area of the plates of capacitive transducers:**

The capacitance of the variable capacitance transducer also changes with the area of the two plates. This principle is normally used for measurement of Angular and linear displacements. A shaft is connected with one of the plate in an angle sensor. As the shaft makes angular movement along with plate, area between the plates keep changing and thus capacitance varies according to the angular change of the plate.

- **Changing distance between the plates of capacitive transducers:**

In these capacitive transducers the distance between the plates is varying with measurable quantity. This is the most commonly used type of variable capacitance transducer. For measurement of the displacement of the object, one plate of the capacitance transducer is kept fixed, while the other is connected to the object. When the object moves, the plate of the capacitance transducer also moves, this results in change in distance between the two plates and the change in the capacitance. The changed capacitance is measured easily and it calibrated against the input quantity, which is displacement. This principle can also be extended to measure pressure, velocity, acceleration etc.

2.3 DIFFERENTIAL CAPACITIVE-SENSOR SYSTEM:

Depending on the application, capacitive sensor can be floating (i.e. sensors in which neither of the electrodes is grounded) or grounded (i.e. sensors in which one of the electrodes is grounded). Based on the properties of the electrode structure and the dielectric material, the electrical properties of capacitive sensors can differ significantly. For instance, they can demonstrate pure capacitive behavior or can have resistive leakage. Their values can range from less than one pF up to hundreds of pF or even to nF. Sometimes their values can change very fast, such as in displacement sensors for servo systems, while in other applications their values can be semi-static. A capacitive Transducer with greater sensitivity and also with immunity to changes in other non measured variables can be obtained by the way of differential capacitive transducer design.

A differential capacitive sensor has two sensing capacitances *C1* and *C2* whose values change in proportion to the parameter being sensed, and the changes in *C1* and *C2* are normally equal and opposite. Since the value of one of the capacitances increases and that of the second capacitance decreases in proportion to the parameter being sensed, differential capacitive sensors are also popularly known as push–pull- type capacitive sensors [1]. A simplified electrical equivalent circuit of a typical differential capacitive sensor is shown in Figure 2.1.

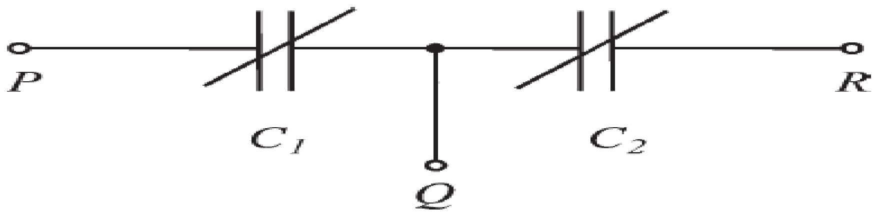

Figure 2.1: Electrical equivalent circuit of a differential capacitive sensor.

If the parameter being sensed alters the area between the plates of the sensor, then such a capacitive sensor will possess a linear input–output relationship, as given by the following:

$$C_1 = C_0(1 \pm kx)$$
$$C_2 = C_0(1 \pm kx) \qquad (2.1)$$

Here, k is the transformation constant of the sensor, and C_0 is the nominal value of C_1 and C_2

when *x,* which is the physical quantity being sensed, is zero. Alternatively, a capacitive sensor that utilizes the distance between the plates as the transduction parameter will possess an inverse relationship, as given by the following:

$$C_1 = \frac{C_0}{(1 \pm kx)}$$

$$C_2 = \frac{C_0}{(1 \pm kx)} \qquad (2.2)$$

2.4 LINEARLY VARIABLE DIFFERENTIAL CAPACITIVE ANGULAR TRANSDUCER (LVDCAT):

The sensor part of the proposed linearly variable differential capacitive angular transducer is shown in Figure 2.2 .This sensor consists of three circular shaped conducting plates mounted concentrically one above another. While the top and bottom plates (TP and BP) are firmly fixed, the middle plate MP, having a semi-circular shape, freely rotates between the top and bottom plates. The bottom plate is made to divide into two semi-circular plates. The top, middle and the bottom plates are electrically insulated from each other. The two, semi circle parts of the bottom plate are identical in dimensions and are insulated from one another.

The circular top plate is positioned such that it is aligned with bottom plate when both of its parts, BP1 and BP2, are place appropriately forming the full circle. The middle, semi circular plate MP is mounted on a spindle and suitably anchored, rotates freely between the top and bottom plates. The spindle attached to the middle plate (MP) is mechanically linked to the element whose angular position θ is to be measured.

The inner and outer radius of top and bottom plates are retained same. But inner and outer radius of the middle plate is made slightly lesser in order to make mechanical connection between middle plate and spindle. If the middle plate (MP) and the two bottom semi circular plates are all kept at the same potential, it nicely turns out that the resulting two capacitances C1 and C2 between lead pairs TP-BP1 and TP-BP2 respectively vary as θ of a pair of plates of a capacitance

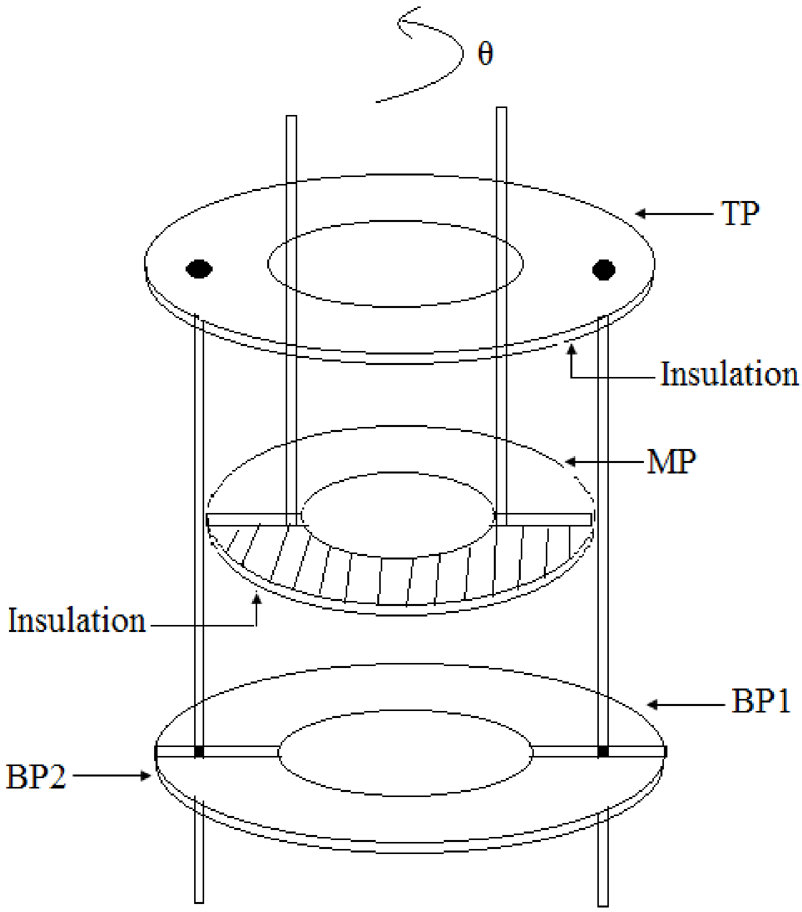

Figure 2.2: Sensor part of LVDCAT.

Visual idea about the movement of middle plate between top and bottom plates of the sensor is shown in figure 2.3. For clarity the top plate, insulating plates and spindles are not shown in the figure. An additional guard ring can be provided to remove the fringing effect of capacitance between top and bottom plate.

Middle plate of the sensor is always connected to ground in this configuration. During Angular rotation of middle plate, when middle plate is exactly between Tp-Bp1, value of C1 will be minimum (C_O) and C1 will have maximum (C_M) value when this middle plate is exactly between Tp-Bp2. The value of C2 will vary in a similar manner with exactly opposite conditions. Thus as θ varies from 0° to 180°, the values of capacitances C1 and C2 will vary linearly resulting in a push-pull or differential pair of capacitances.

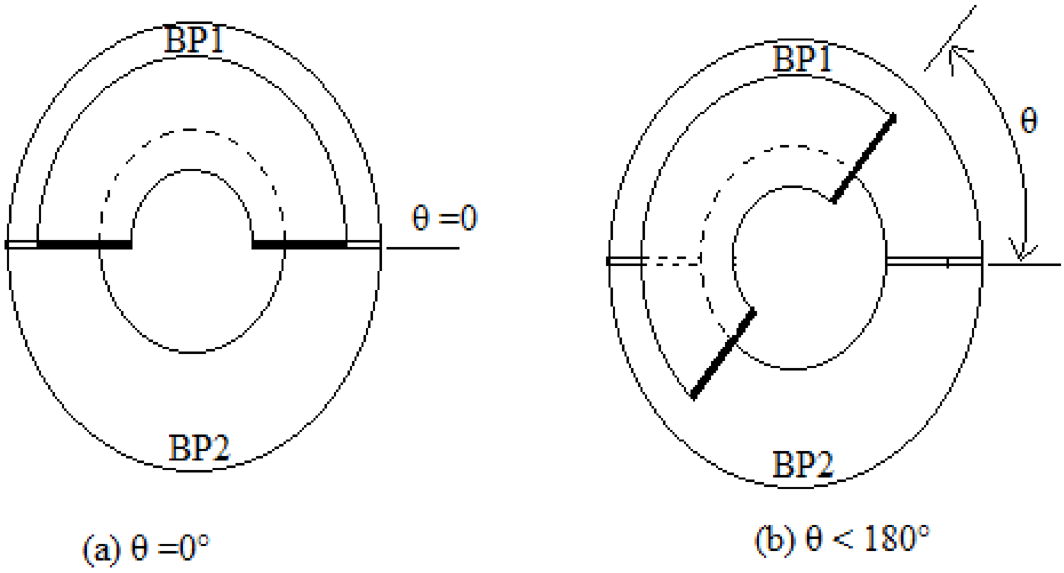

Figure 2.3: Top view of the sensor showing middle plate at different positions.

Mathematically the variation of capacitances C1 and C2 in terms of θ can be expressed as:

$$C_1 = C_O + (C_M - C_O)\left(\frac{\theta}{180}\right)$$
$$C_2 = C_O + (C_M - C_O)\left[1 - \left(\frac{\theta}{180}\right)\right] \quad (2.3)$$

Graphical representation of the equation 2.3 is provided in Figure 2.4. It is easily seen from the Figure 2.4, that the value of the capacitance C1 increasing from C_O to C_M in the interval 0°< θ < 180° and simultaneously the value of capacitance C2 is decreasing from C_M to C_O where C_M is the maximum capacitance and C_O is minimum capacitance. Assuming C0 to be equal to zero, the value of (C1-C2) is continuously increasing from $-C_M$ to C_M. If (C1-C2) is divided by (C1+C2) we will get a linear plot ranging from -1to 1. By adding 1 to the previous plot a final plot is deduced which gave linearly varying function with respect to θ.

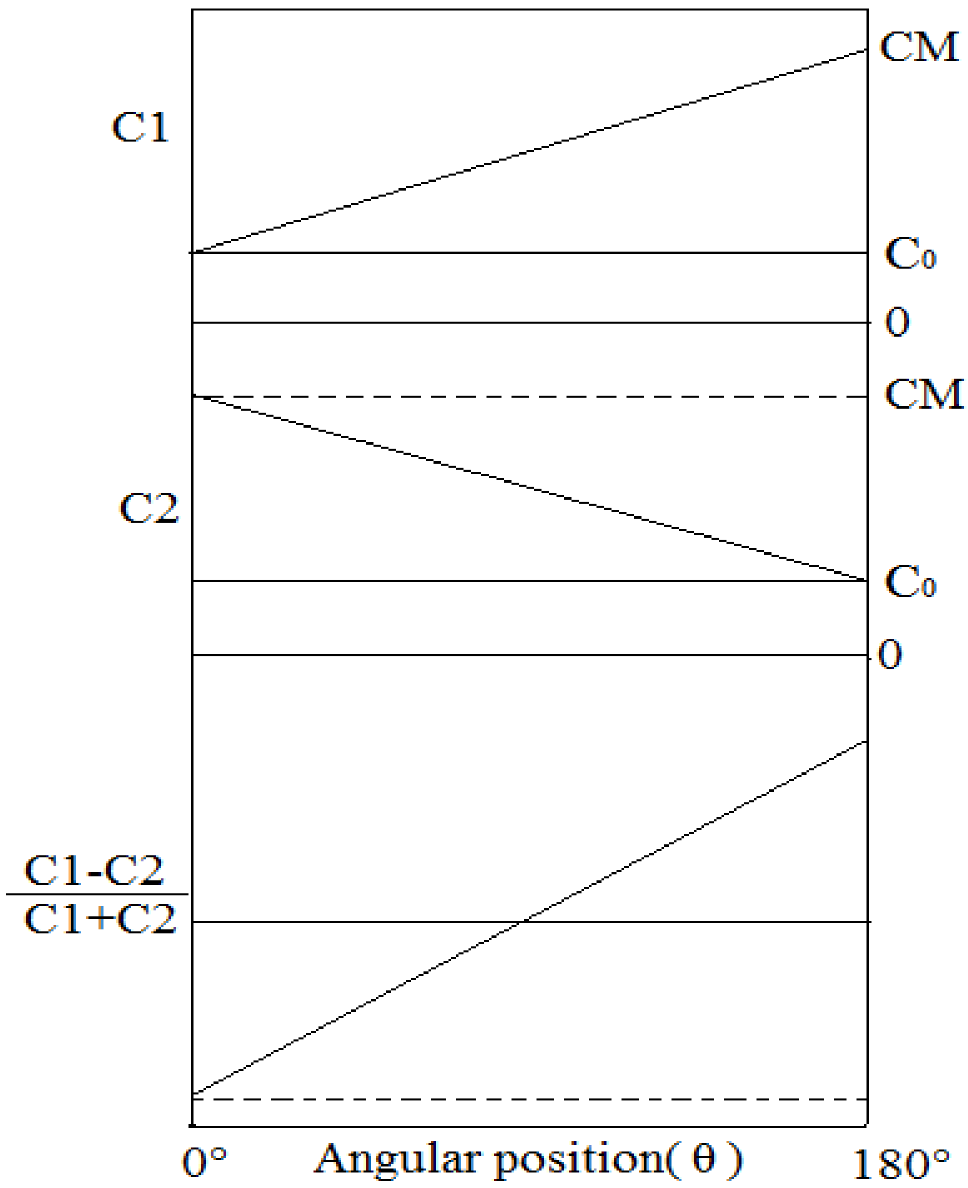

Figure 2.4: Variation of sensor capacitances C1 and C2 and linear function with θ.

2.5 SENSOR FABRICATION

The sensor is fabricated using three single sided copper clad boards. The copper of these boards acts as electrodes of the capacitor. The board material here is FR-4 (FR stands for flame resistant) which acts as insulator between the electrodes of the capacitive sensor.

These copper clad boards were cut by the lathe machine in circular disc shapes of required dimensions. The specifications of the sensor are depicted in Table 2.1.

Electrode Material	Copper
Insulator	FR-4(Flame Resistant-4)
Electrode thickness	30µm
Insulator thickness	0.8mm
Dielectric Constant of FR-4	4.8
Inner radius of top plate	2.8cm
Outer radius of top plate	3.8cm
Inner radius of middle plate	1.8cm
Outer radius of middle plate	3.8cm
Inner radius of bottom plate	2.8cm
Outer radius of bottom plate	3.8cm

Table 2.1: Specifications and dimensions of the sensor.

The copper of middle plate is then etched using ferric chloride (etchant) in order to make it semi circular disc like shape. Middle plate is provided with four screws, nuts and washers with the help of which angular rotation of the middle plate is made possible. The snapshot of the middle plate is given figure 2.5.

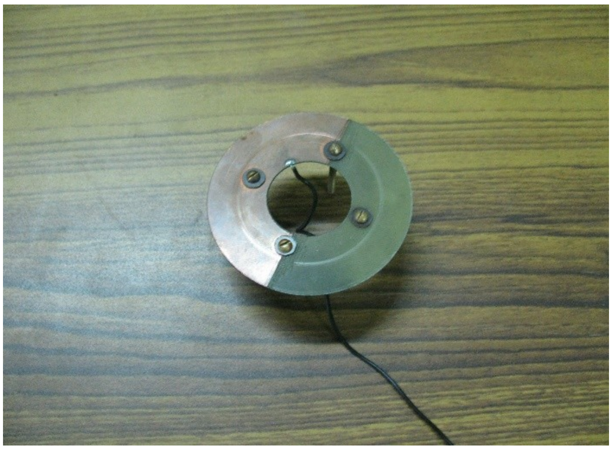

Figure 2.5: Middle plate

Similarly a strip of copper is removed from the bottom plate with the help of square file in the mechanical workshop in order to divide it into two identical semi circular parts. Two wires are finely soldered with it to take out the connections. Snap shot of the bottom plate with lead wire is placed as Figure 2.6.

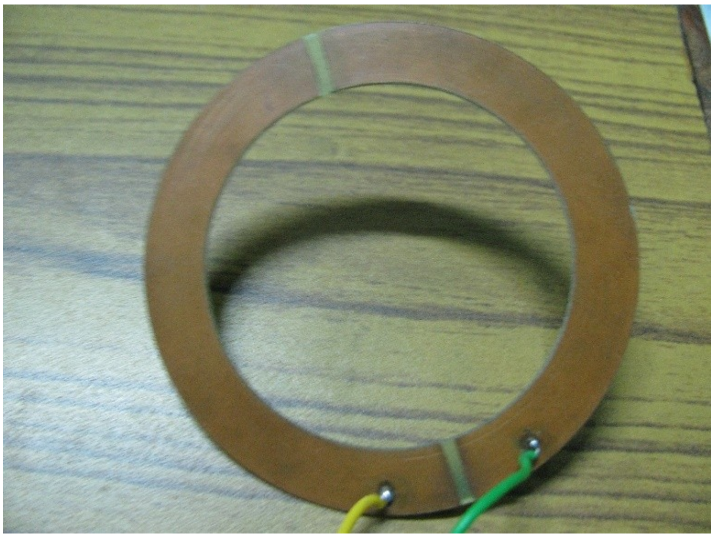

Figure 2.6: Bottom plate

These circular copper clad boards are then placed inside a plastic case provided by the manufacturer of an automobile brake system. The size of the plastic case resemble with the size of the brake shoe wear indicator sensor being used in the company. The bottom plate and top plate is fixed inside the plastic case with the help of glue. Holes are made on the plastic case to take out finely soldered lead wires from top and bottom plates. To measure the angle, image of a protractor has been pasted on the plastic case. The snap shot of the angle sensor is placed as Figure 2.7

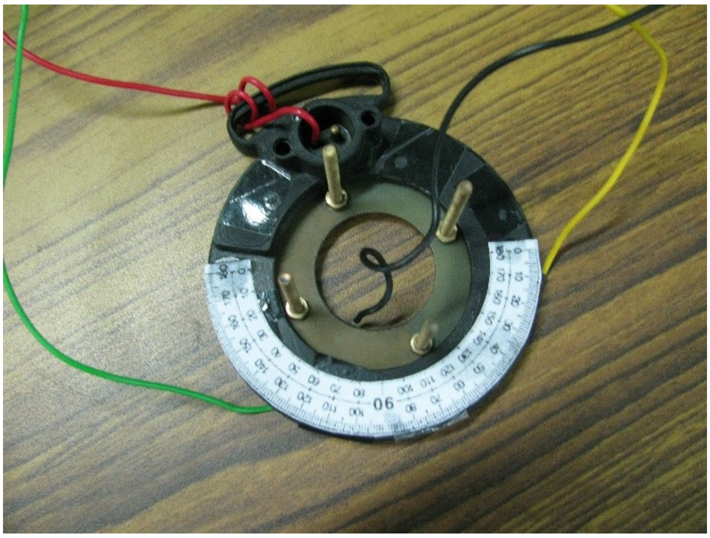

Figure 2.7: Angle Sensor

2.6 CHALLENGES FACED DURING SENSOR FABRICATION:

Many challenges were observed during sensor fabrication right from procuring proper materials, availability of lathe machines, non availability of ferric chloride etchant etc. Important Challenges/issues faced are mentioned below.

a. Fine soldering of Lead wires and breakage of lead wire at soldering Joint:

Lead wires are required to be soldered precisely on to all the plates. These lead wires were getting cut at the soldering joints from both bottom plate and top plates.

Solution: Lead wires were fixed on the plastic case itself with cello taps and glues. This arrangement avoided forces getting transferred to soldering joints of lead wires on the bottom and top plate. The similar problem was occurring due to relative motion between top and middle plate and to avoid this top plate was fixed firmly to the plastic case with the help of glue.

b. Lateral movement of the middle plate were observed:

Lateral movement of Middle plate was observed after inserting all the plates inside the plastic case. This movement can create non linearity in the variation of capacitance and hence this movement has to be arrested.

Solution: To arrest this, four washers of appropriate dimensions were used with screws attached to the middle plate. These washers move by touching the surface of the plastic case to avoid the lateral movement of the middle plate.

c. Removal of fine layer of copper from Bottom plate:

Initial idea of removal of copper was using ferric chloride etchant. There was a possibility of copper getting removed from other part as the thickness of the copper is extremely small on this plate.

Solution: This issue was resolved by removing small layer of copper with the help of a thin square file from the mechanical workshop.

CHAPTER 3: SIGNAL CONDITIONING CIRCUIT

3.1 INTRODUCTION

To obtain a measurable output relative to the parameter being sensed by a capacitive sensor (Angle sensor), a signal-conditioning circuit that converts the variations in the sensor capacitances *C1* and *C2* to a proportional analog voltage or current is required [2].

Digital instrumentation systems are preferred over analog systems as they offer better user interface and excellent processing power. Analog-signal-conditioning circuit cascaded to an analog-to-digital converter (ADC) is to interface a sensor to a digital instrumentation system, an. A typical ADC will possess an analog part and a digital part. In direct Digital Converters, ADC logic appropriately modified to provide a digital output directly proportional to the parameter being sensed and requirement of a separate analog-signal-conditioning unit can be avoided. A Direct Digital Converter (DDC) suitable for a differential resistive sensor has been reported [3]. For single element capacitive Sensors, there are methods based on a sigma–delta modulator [4], auto-ranging [5], and duty cycle variation [6]. For differential capacitive arrangement, there are Digital Converters which provide an output proportional to the ratio of two capacitances. This method is limited to a small range of variations in the capacitances of the sensor [7]. A charge-balancing-type capacitance-to-digital converter (CDC) reported earlier employs a very complicated switching arrangement [8]. The successive approximation-type CDC that uses the well-known successive approximation register structure requires a high-precision digital-to-analog converter [9]. ICs AD7746 and AD7747 marketed by Analog Devices Inc. are CDCs that convert single or differential capacitances to an equivalent digital output utilizing the sigma–delta principle [10]. Since the output of AD7746/AD7747 is dependent on the nominal values of the sensor capacitances, as they do not employ the ratio-metric method, additional processing is required if an output directly proportional to the parameter being sensed is required. Moreover, these ICs can accept capacitances only up to 21 pF and have an active but limited compensation range over which the effect of stray capacitances on the output can be nullified.

A switched-capacitor dual-slope technique based on a ratio-metric approach that converts the variations in the capacitances *C1* and *C2* of a differential capacitive sensor directly into a proportional digital value is known as Dual slope Capacitance to Digital Converter (DSCDC) is used as a signal conditioning circuit. The conversion time of DSCDC is 33% less than that of the triple slope CDC. DSCDC has negligible sensitivity toward various error sources, such as stray capacitances, switch leakage currents, and op-amp offset voltage, in comparison with the triple-slope CDC. This method requires only a single dc reference voltage and hence avoids errors arising out of mismatched dc reference voltages (offset voltage) of opposite polarity, which is a major source of error in the triple-slope CDC. Hence DSCDC is selected for processing the signals from designed angle sensor.

3.2 DUAL SLOPE CAPACITANCE TO DIGITAL (DSCDC) CIRCUIT:

The circuit consists of an integrator, comparator, Control and Logic Unit (CLU), three switches and differential capacitance Sensor. The functional block diagram of the signal conditioning circuit is shown in Figure 3.1

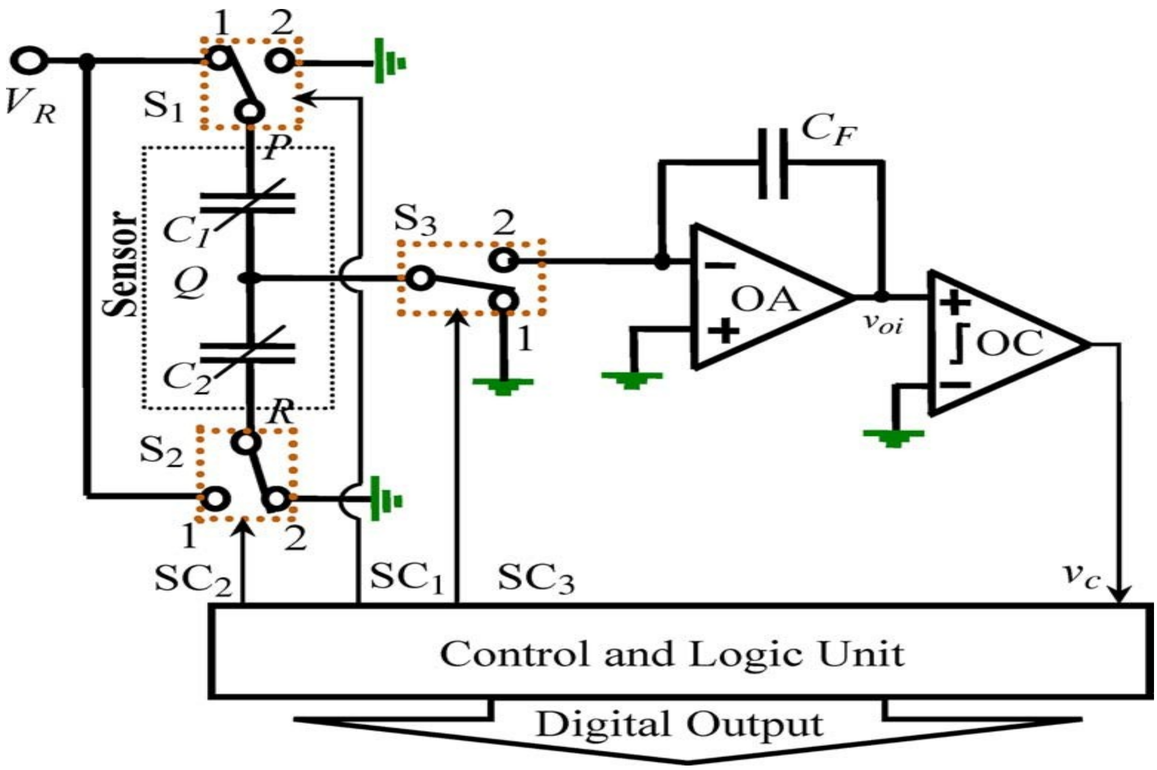

Figure 3.1: Signal Conditioning Circuit [1].

3.3 PRINCIPLE OF WORKING:

The circuit is made of an integrator and a control and logic unit (CLU) incorporating an n-bit or N-digit timer counter. As indicated in Figure 3.1, the sensor capacitances C1 and C2 in combination with three single-pole double-throw (SPDT) switches S1, S2, and S3, op-amp OA and the feedback capacitor CF form a switched-capacitor integrator. The comparator senses status of the output of the integrator. The output Vc of the comparator will be high for the output of the integrator Voi ≥ 0, otherwise comparator output will be low. A high-to- low or low-to-high transition on Vc indicates that the output Voi is crossing through zero. The CLU performs integration & a de-integration for a complete conversion cycle by varying the switch positions through control lines SC1, SC2, and SC3, as per the status of the output (Vc) of the comparator. The operational logic of the CLU is timed by a clock signal possessing a period TC and 50% duty cycle. CLU performs an auto-zero function to force the integrator output to zero to ensure an appropriate initial condition before the start of a conversion cycle.

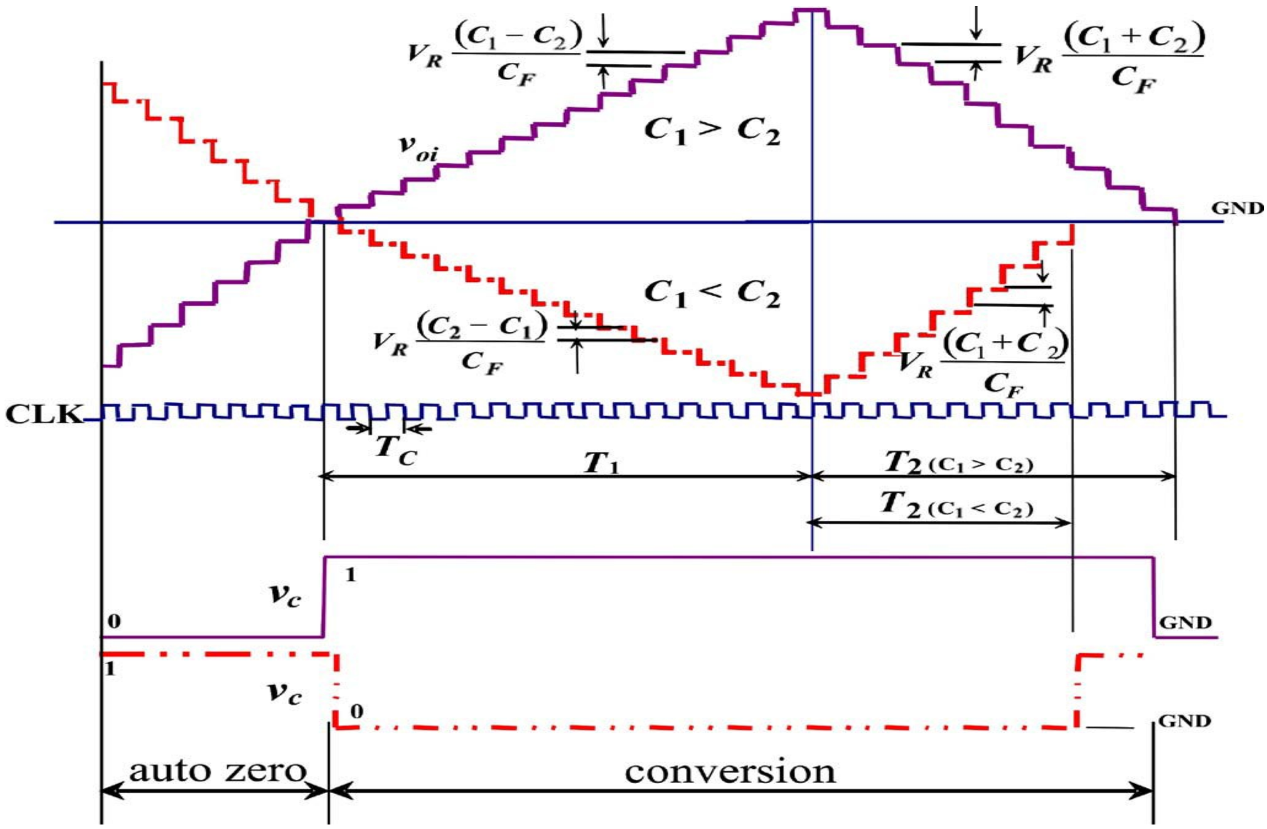

Figure 3.2: Integrator output Voi and the comparator output Vc for (solid line) C1 > C2 and (dotted line) C1 < C2. In the auto-zero phase, the integrator voltage is assumed to be positive for C1 < C2, and vice versa [1].

3.3.1 Auto-Zero Phase

The output voltage of the integrator has to be zero before the start of first integration periode. There are different ways for doing this like shorting C_f with switch placed across the feedback capacitor. This method is not preferred as this will introduce error due to offset voltage of the comparator. This is achieved with the help of auto zero function. Flow chart of auto zero phases is given in Figure 3.3.

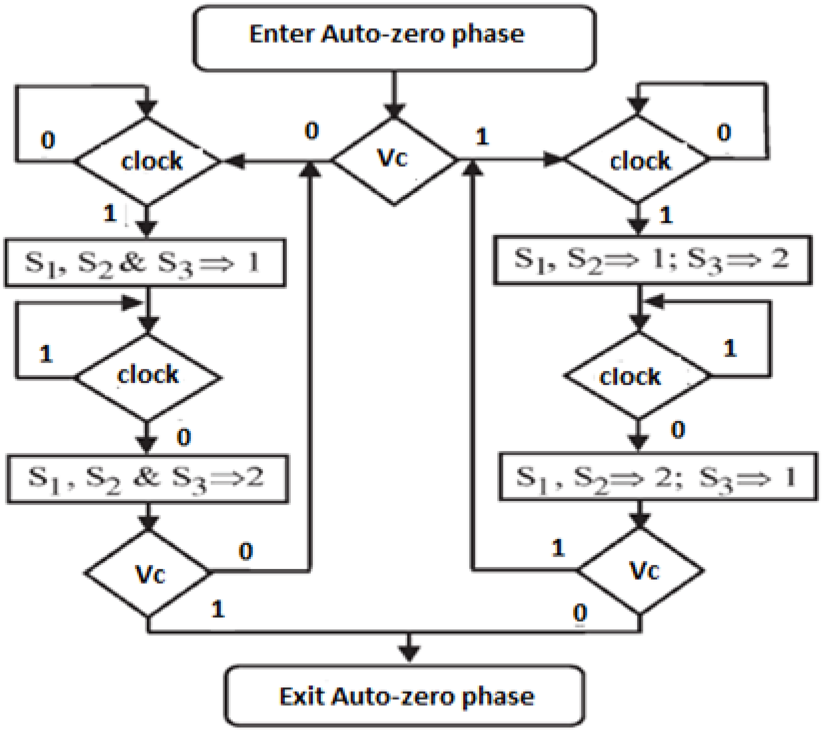

Figure 3.3: Flowchart of the auto-zero phase [1].

In the auto-zero phase, comparator output voltage is sensed by CLU and switch positions are adjusted through controlling lines SC1, SC2, and SC3. The required switch positions along with condition of Vc and clock positions are given below such that output of integrator goes to zero at the end of this phase.

If Vc *is* high:

a) CLU logic is designed to set S1 and S2 to be in position 1 and *S3* to be in position 2 for a period TC/2 (whenever the clock is high).
b) When the clock turns low (at the end of TC/2), all three switches are toggled (S1 and S2 TO position 2 and S3 to Position 1) and kept in that position for the next TC/2.

If Vc is low :

a) CLU logic sets S1, S2, and S3 to be in position 1 for a period TC/2
b) CLU toggles all the switches(S1,S2&S3 to position1) and keeps them in the toggled position for the next TC/2

The above switching arrangement will make output of the integrator to ramp up/down with a step voltage of $\Delta v = VR(C1 + C2)/CF$ for every clock cycle to reach zero at the end of this phase. When Voi reaches zero, the comparator output Vc will transit from high to low or Low to high and this transition is detected by CLU to enable beginning of conversion phase.

3.3.2 Conversion Cycle

A typical conversion cycle consists of an Integration and de integration time periods, i.e., T1 and T2 respectively. The quantity to be measured will be proportional to the period T2, whereas period T1 is a preset value. CLU senses comparator output Vc and controls switch positions so that integration and de integration are performed during this periode. The required switch positions along with the condition of Vc and clock positions are given below for this conversion phase.

During T1, **If Vc *is* high:**

a) when the clock is high (TC/2), switch S2 is set at position 2, and switches S1 and S3 are set to position 1
b) When the clock turns low, switch S2 is changed to position 1, and S1 and S3 are set to position 2

During T2, **If Vc *is* high:**

a) whenever the clock is high, switches S1 and S2 to position 1 and S3 to position 2
b) when the clock turns low, switches S1 and S2 to position 2 and S3 to position 1

During T2 , If Vc low

a) whenever the clock is high CLU switches S1, S2, and S3 to position 1
b) whenever the clock is high CLU switches S1, S2, and S3 to position 2

During T1 whenever the clock is high, C1 will charge to VR, and C2 will get discharged to ground. As soon as the clock goes low, the charge in C1 will be transferred to CF, and at the same time, the charging current of C2 is also sent into CF. Hence, the differential charge between VRC1 and VRC2, i.e., VR (C1 − C2), will get transferred to CF for every clock cycle. If C1 > C2, then Voi ramps in the positive direction in steps of value VR (C1 − C2)/CF for every clock period TC, as indicated by the solid line in Figure 3.2. On the other hand, if C2 > C1, then Voi will ramp in the negative direction in steps of value VR (C2 − C1)/CF for every clock, as indicated by the dotted line in Figure 3.2. If C1 = C2, then the differential charge transferred to CF for every clock is zero; hence, at the end of T1 (= N1TC, with N1 being a preset integer), the output of integrator *Voi* will remain zero.

During T2, if the comparator output Vc at the end of T1 is high (i.e., C1 > C2) and also during high clock period both C1 and C2 will get charged to VR, and their charging currents will discharge CF by VR (C1 + C2). When the clock goes low, the sensor capacitances are discharged to ground. This process is repeated for every clock cycle. Hence, the output of the integrator gradually decreases in steps of VR (C1 + C2)/CF and reaches zero.

During T2, if Vc is low at the end of T1 (i.e., C2 > C1), when the clock is high, both C1 and C2 will get charged to VR and when the clock goes low, their net charge VR (C1 + C2) is transferred to CF, discharging it. Under this condition, *Voi* increases in steps of VR (C1 + C2)/CF and reaches zero, as indicated by the dotted line in Figure 3.2. CLU detects transition in the comparator output at the end of periode T2 and number of count corresponding to the periode T2 is measured. At the end of periode T2, net charge across the feedback capacitor is zero. Hence by charge balance equation we can write as

$$\frac{V_R\left(\frac{C_1 - C_2}{C_F}\right)T_1}{T_C} = \frac{V_R\left(\frac{C_1 + C_2}{C_F}\right)T_2}{T_C} \tag{3.1}$$

Rearranging the terms, we get

$$T_2 = \left(\frac{C_1 - C_2}{C_1 + C_2}\right)T_1 \tag{3.2}$$

If the number of clock cycles in T1 and the number of clock cycles measured during T2 are denoted as N1 and N2, respectively, then

$$N_2 = \left(\frac{C_1 - C_2}{C_1 + C_2}\right)N_1 \tag{3.3}$$

Substitution of the values for *C1* and *C2,* as given in (2.3), into (3.3) results in the following:

$$\theta = \left(\frac{N_2}{KN_1}\right)90 + 90 \tag{3.4}$$

Where K= ((C_M -C_O)/(C_M +C_O))is the transformation constant of the Sensor

It nicely turns out that substitution of the values for C1 and C2 for a sensor possessing inverse relationship, as given in (2.2), into (3.3) also results in (3.4). The polarity of θ is taken as positive if *Vc*= 1 at the end of T1. Otherwise, the polarity is treated as negative, as shown in Figure 3.4. SinceN1 is a preset value and k is the sensor's transformation constant, the digital value N2 directly represents the quantity θ being sensed by the sensor. The digital output N2 will be linearly related to θ as given in (3.4), even if C1 and C2 are governed by the inverse relationship, as given in (2.2). This value of θ is displayed on the Arduino software. DSCDC is not only applicable for differential capacitive sensors possessing linear characteristics but also sensors possessing inverse characteristics without any change. The flow chart showing the logic of conversion phase is given in Figure 3.4.

DSCDC is less sensitive to stray capacitance and comparator offset. These parameters have a negligible effect on the output. The effect on the output due to Opamp bias current, switch leakage current and On resistance of the switches are minimized with appropriate selection clock frequency and switch. The error introduced due to uncertainty in the supply voltage is taken care by using the reference voltage from a precision LM 385 IC.

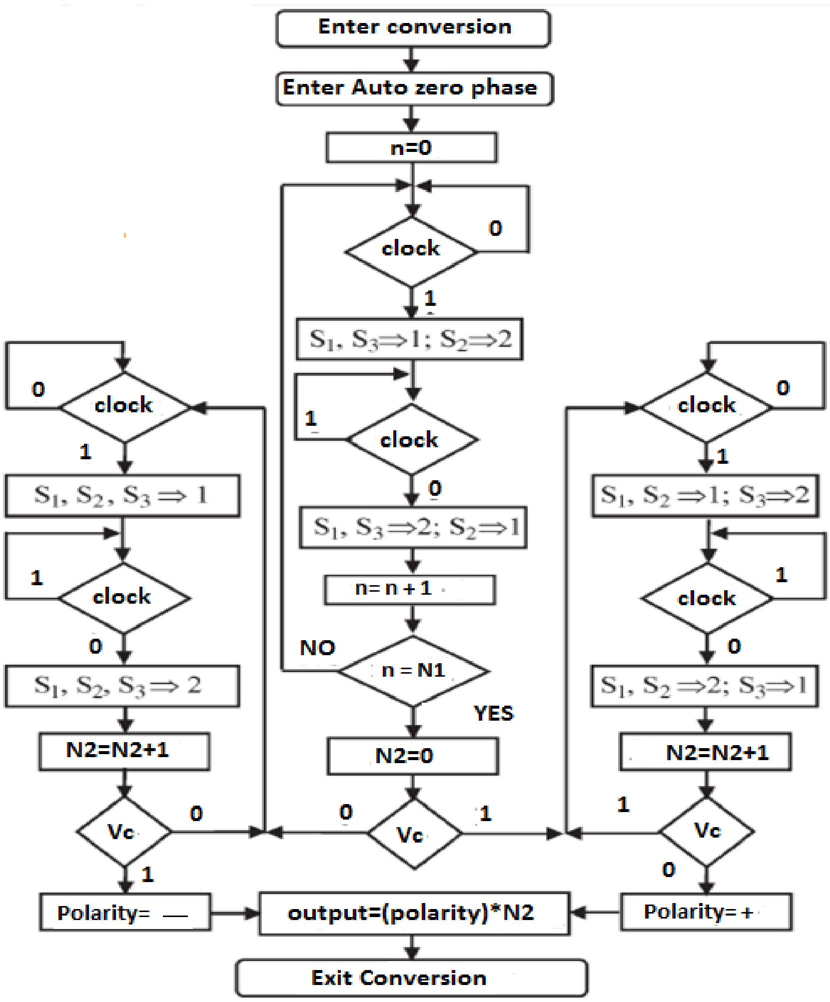

Figure 3.4: Flowchart showing the logic of the conversion phase [1].

CHAPTER 4: HARDWARE SET UP FOR EXPERIMENT

4.1 INTRODUCTION

The methodology used for the angle sensing is represented in the form of a block diagram in Figure 4.1. The angle sensor in the first block was fabricated as explained in section 2.5. The signal conditioning circuit was built on NI Elvis II board, manufactured by National Instrument. ATmega 328 microcontroller along with Arduino UNO was used as the control unit for controlling the switches and also for displaying the angle after required mathematical calculations. This chapter describes in detail about hardware set up such as NI ELVIS II and ARDUINO UNO board used for the experiment.

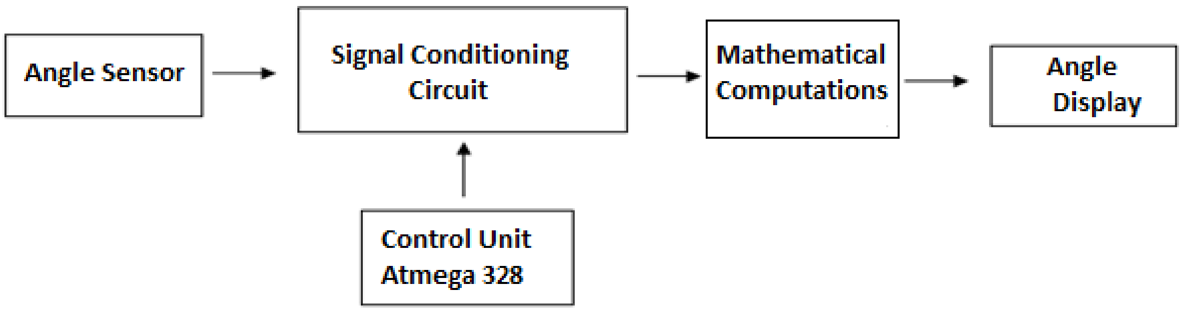

Figure.4.1: Block Diagram.

4.2 NI ELVIS II

The National Instrument's Educational Laboratory Virtual Instrumentation Suite II (NI ELVIS II) is a LabVIEW and computer based design and prototyping environment. NI ELVIS II consists of a custom-designed bench top workstation, a prototyping board, a multifunction data acquisition device and LabVIEW based virtual instruments [11]. This combination provides an integrated, modular instrumentation platform that has comparable functionality to the DMM, Oscilloscope, Function Generator, and power Supply found on the laboratory workbench [11].

The NI ELVIS II Workstation can be controlled either vi manual dials on the stations front or through software virtual instruments. The NIELVIS II provides full testing, measurement, and data logging capabilities by setting up an environment of virtual instruments. This can perform functions similar to a number of much more expensive instruments used in the lab. NI ELVIS II find applications in engineering, physical sciences, and biological sciences laboratories. NIELVIS II consists of a Bench top hardware workspace and NI Elvis software. Bench top hardware workspace for building circuits is shown in Figure 4.2 and NI Elvis software interface consisting of twelve soft front panels (SFP) instrument is shown in Figure 4.3. [11]

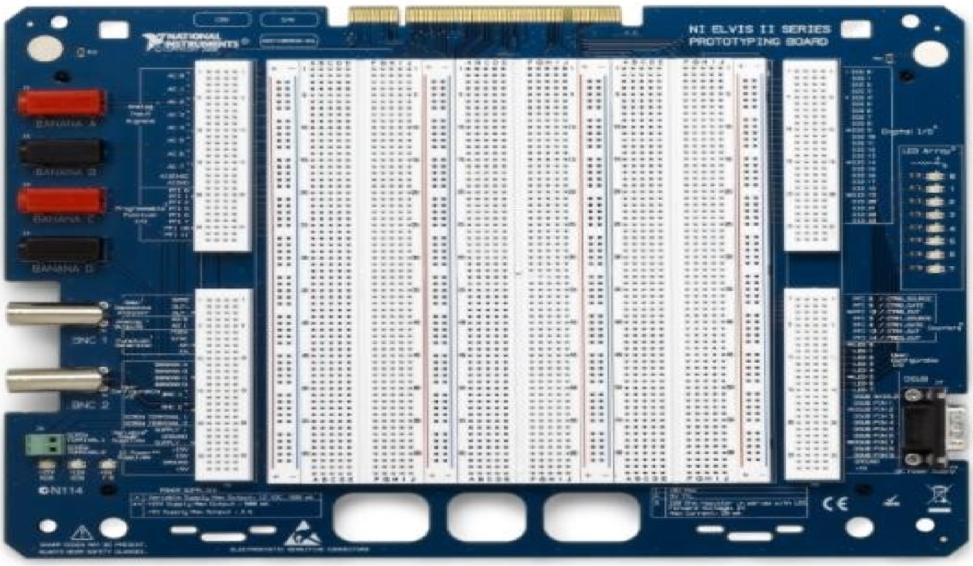

Figure 4.2: NI ElVIS II hardware [11].

Figure 4.3: NI ELVIS II Soft Panel [11].

4.2.1 NI ELVIS II HARDWARE:

NI ELVIS II hardware consists of a Bench top Workstation and a Series Prototyping Board.

Bench top Workstation: A work station has a top panel, a Rear panel and a bottom panel. Series prototyping board is fixed on the top panel. The workstation control panel provides easy-to-operate knobs for the variable power supplies and function generator, as given in Figure 4.2, and offers convenient connectivity and functionality in the form of BNC and banana-style connectors, shown in Figure 4.2 to the function generator, scope, and DMM instruments at the left side of the bench top.

Series Prototyping Board: The NI ELVIS II Series Prototyping Board is connected to the bench top workstation. The prototyping board provides an area for building electronic circuitry and has the necessary connections to access signals for common applications. Figure 4.4 shows the prototyping board connected on a bench top work station with a brief description. Multiple prototyping boards can be used interchangeably by removing it from the bench top workstation. It is possible to install a custom prototype board with help of the prototyping board connector available on NI ELVIS II. This connector is mechanically the same as a standard PCI connector.

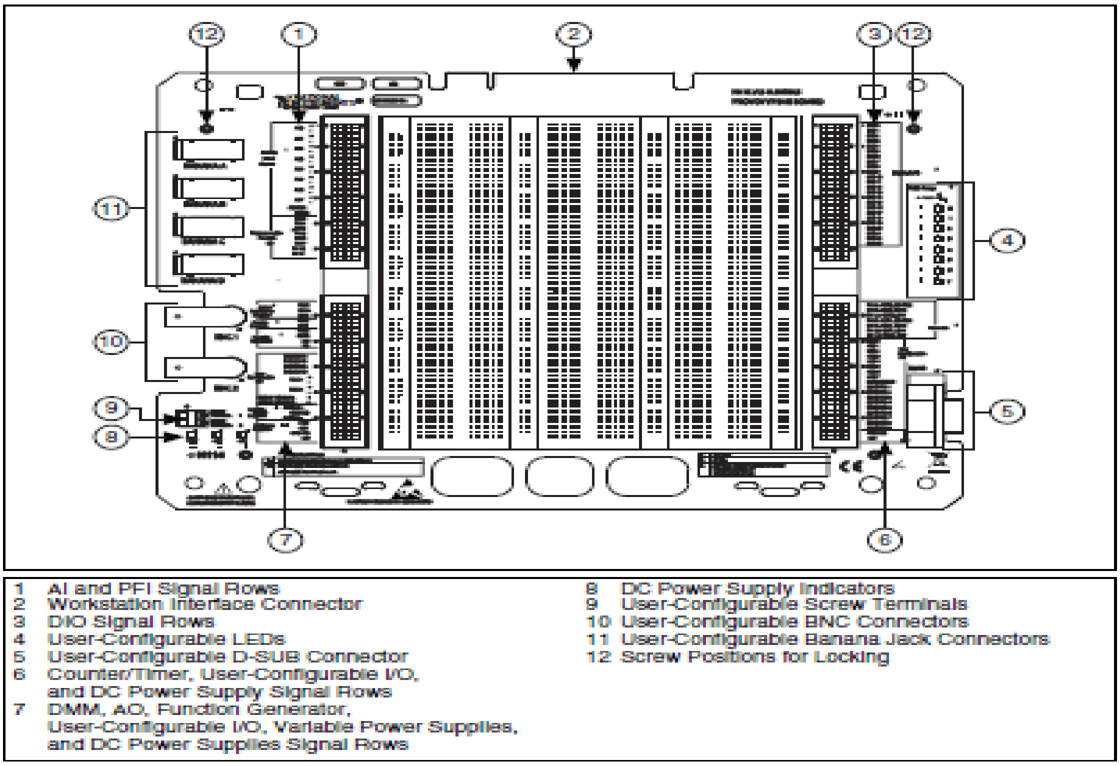

Figure 4.4: Series Protyping Board [11].

4.2.2 NI ELVIS II Software:

The NI ELVISmx software is created in LabVIEW, takes advantage of the capabilities of virtual instrumentation. The software includes Software Front Panel (SFP) instruments, LabVIEW Express VIs, and Signal Express blocks for programming the NI ELVIS II Series hardware [11]. The SFP instruments launcher software panel consists of following instruments:

• **Digital Multimeter (DMM)**: This instrument can measure Voltage (DC and AC), Current (DC and AC), Resistance, Capacitance, Inductance and Diode test Audible continuity.

• **Oscilloscope (Scope):** This instrument provides the functionality of the standard desktop oscilloscope and it has two channels and provides scaling and position adjustment knobs along with a modifiable time base.

• **Function Generator (FGEN)**: This instrument generates standard waveforms with options for the type of output waveform (sine, square, or triangle), amplitude selection, and frequency settings.

• **Variable Power Supply (VPS):** Output of the positive or negative variable power supply can be controlled with this SFP instruments.

• **Bode Analyzer**: A full-function Bode Analyzer is available by combining the frequency sweep feature of the function generator and the Analog Input (AI) capability of the device.

• Dynamic Signal Analyzer (DSA): This instrument performs a frequency domain transform of the AI or scope waveform measurement.

• Arbitrary Waveform Generator (ARB): This advanced-level SFP instrument uses the capabilities of Analog Output (AO) and Waveform Editor Software to create various signals.

• Digital Reader (DigIn) and Digital Writer (DigOut): These instruments read digital data from NI ELVIS and update its Series digital lines with user-specified digital patterns.

• **Impedance Analyzer:** This instrument is a basic impedance analyzer that is capable of measuring the resistance and reactance for passive two-wire elements at a given frequency.

• **Two –wire and Three –wire Current-Voltage Analyzer**: These instruments can be used to conduct diode and transistor parametric testing and view current-voltage curves.

4.3 ARDUINO PLATFORM

Arduino is an open source electronics prototyping platform based on flexible hardware and software. Arduino boards are inexpensive and can work with Windows, Macintosh OSX & Linux operating systems unlike other microcontroller platforms. The Arduino software and Hardware can be improved by the experienced professional as it is published as open source tools. There are various types of Arduino microcontroller board available in the market including the Arduino kits, Arduino Uno Board and Arduino shields [12].

4.3.1 Arduino Uno Board

Arduino Uno is one of the microcontroller boards manufactured by the Arduino and it is a microcontroller board based on the Atmel's ATmega328 microcontroller .Uno board is the latest in a series of USB (Universal Serial Bus) Arduino boards which is the reference model for the Arduino platform. The Arduino Uno board has a 16 MHz ceramic resonator, a USB connection, a power jack, an ICSP header, a reset button, 6 analog inputs and 14 digital input/output pins (of which 6 can be used as PWM outputs). The board has 32 KB flash memory of which 0.5 KB is used by boot-loader, 2 KB of SRAM, 1 KB of EEPROM and 16 MHz clock speed [13].

Figure 4.5 shows the Arduino Uno Board. It can be powered via a USB connection or with an external power supply. As can be seen in Figure 4.5, pins A0 to A5 are the analog input pins, pins 0 to 13 are 14 digital input/output pins and the pins with a "~" sign can be used as the PWM output pins. The digital pins can be used as input or output pins by selecting the mode by using the function pin-mode () and then using the function digitalRead() or digitalWrite() according to the program requirement. Pins 0(RX) and 1(TX) are used for serial communication while pins 10(SS), 11(MOSI), 12(MISO) and 13(SCK) are used for SPI (Serial Peripheral Interface) communication. In addition to pin 0 and 1, a Software Serial library allows serial communication on any of the Uno's digital pins [13].

Figure 4.5: The Arduino Uno Board [13]

4.3.2 ATmega328 Microcontroller:

The microcontroller is a low-power CMOS (Complementary Metal Oxide Semiconductor) 8-bit microcontroller based on the AVR enhanced RISC (Reduced Instruction Set Computer) architecture. The powerful execution of instructions in a single clock cycle leads to the achievement of 1 MIPS per MHz throughputs allowing the designer to optimize power consumption versus processing speed [14].

The internal architecture of the microcontroller is shown in Figure 4.6. The central processing unit (CPU) is the brain of the microcontroller which controls the execution of the program. The MCU (Microcontroller unit) consists of 4K/8K bytes of in-system programmable flash with read- while-write capabilities, 256/412/1K bytes EEPROM along with the 512/1K/2K bytes of SRAM. Along with this, the MCU consists of many other features [14]:

- 23 general purpose I/O lines and 32 general purpose working registers
- 3 flexible timer/counters with compare modes, internal and external interrupts and a serial programmable USART
- A byte-oriented 2-wire serial interface, an SPI serial port, a 6-channel 10-bit ADC (8 channels in TQFP and QFN/MLF packages), a programmable watch-dog timer with an internal oscillator and 5 software-selectable power saving modes [14].

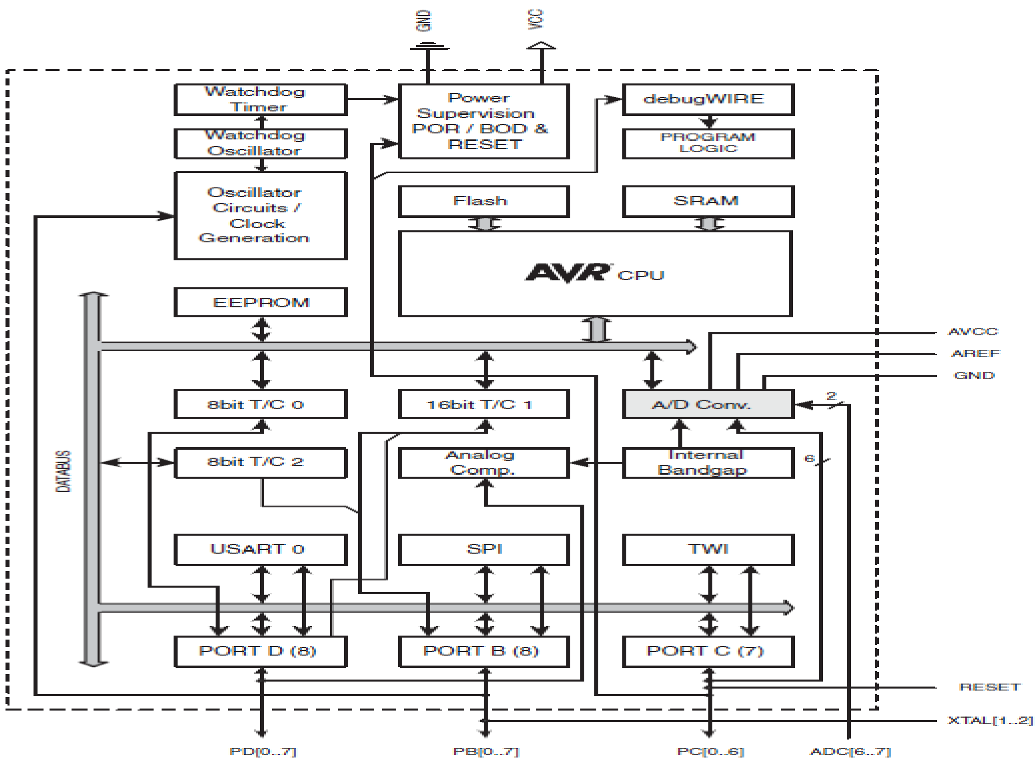

Figure 4.6: ATmega328 Microcontroller Architecture [14].

There are five types software selectable Power saving modes. Powers saving modes are Idle mode, Power-down mode, Power- save mode, ADC Noise Reduction mode and the Standby mode. As mentioned earlier, CPU is the brain of the microcontroller which controls the execution of the program. Therefore the CPU is able to access the memories, perform calculations, control peripherals and handle interrupts. The AVR uses the Harvard architecture with separate memories and buses for program and data to maximize the performance as well as the parallelism. The principle of execution of instructions in the program memory is the single-level pipelining. The concept of pre-fetching the next instruction while executing one instruction enables the instructions to be executed in every clock cycle and the program memory is in the System Reprogrammable Flash memory [14].

- **AVR CPU Core**

The block diagram of AVR CPU Core architecture is shown in Figure 4.7 The main function of the CPU core is to ensure correct program execution. The CPU must therefore be able to access memories, perform calculations, control peripherals, and handle interrupts. AVR uses Harvard architecture with separate memories and buses for program and data to maximize performance and parallelism. Single level pipelining is used to execute instructions in the program memory. When one instruction is executed, the next instruction is being pre-fetched from the program memory. This concept enables to execute instructions in every clock cycle. The program memory is In-System Reprogrammable Flash memory.

Arithmetic Logic Unit (ALU) supports arithmetic and logic operations between registers or between a constant and a register. ALU can perform single cycle operation, as fast-access Register File contains 32 x 8-bit general purpose working registers with a single clock cycle access time. Status Register is updated after an arithmetic operation to reflect information about the result of the operation. Program flow is provided by conditional and unconditional jump and call instructions, able to directly address the whole address space. Most AVR instructions have a single 16-bit word format. Every program memory address contains a 16- or 32-bit instruction.

Program Flash memory space is divided in two sections, the Boot Program section and the Application Program section. Both sections have dedicated Lock bits for write and read/write protection. The SPM instruction that writes into the Application Flash memory section must reside in the Boot Program section.

During interrupts and subroutine calls, the return address Program Counter (PC) is stored on the Stack. The Stack is effectively allocated in the general data SRAM, and consequently the Stack size is only limited by the total SRAM size and the usage of the SRAM. The Stack Pointer (SP) is read/write accessible in the I/O space. The data SRAM can easily be accessed through the five different addressing modes supported in the AVR architecture. The memory spaces in the AVR architecture are all linear and regular memory maps.

A flexible interrupt module has its control registers in the I/O space with an additional Global Interrupt Enable bit in the Status Register. All interrupts have a separate Interrupt Vector in the Interrupt Vector table. The interrupts have priority in accordance with their Interrupt Vector position. The lower the Interrupt Vector address, the higher the priority.

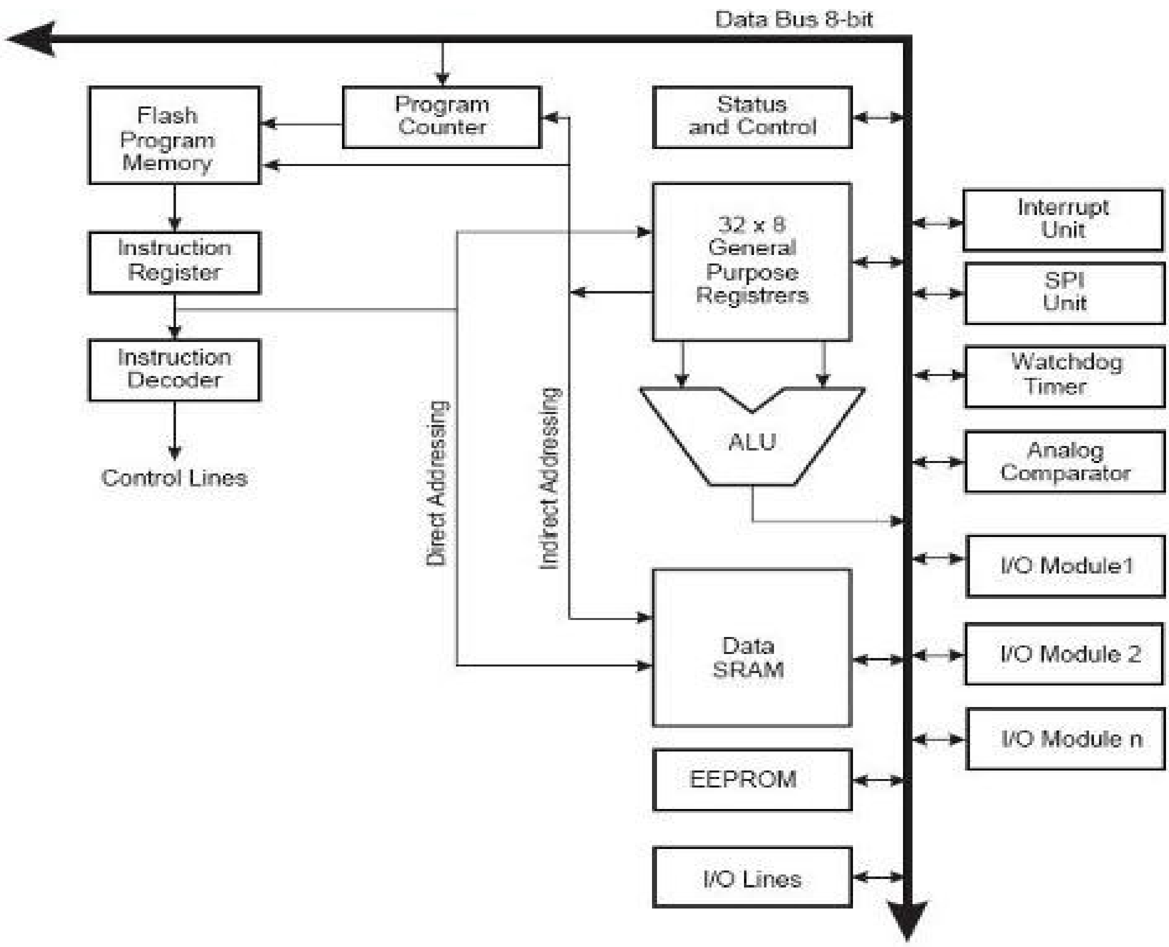

Figure 4.7: Block diagram of the AVR CPU Core architecture [14].

CHAPTER 5: EXPERIMENTAL SETUP AND RESULTS

5.1 EXPERIMENTAL SET UP:

In order to demonstrate the practicality of the proposed transducer, a prototype unit was built on the NI Elvis board and tested. Angle sensor, fabricated as given in 2.5, is used as C1 and C2 in the Dual Slope Capacitance to Digital Converter (DSCDC) Circuit. Precision reference voltage *VR* was derived from LM 385 IC. Supply voltages to the integrator, comparator, Arduino Uno board and switch were provided from the ELVIS board. HCF 4053 IC manufactured by ST Microelectronics was used to realize switches *S1, S2 & S3.* LF347 served as the opamp OA and the comparator OC. Polystyrene capacitor is selected as feedback capacitor and value was chosen to be $2.26nF$. The CLU was realized with ARDUINO UNO board consisting of ATmega328 as microcontroller. A suitable program was written and burnt into the microcontroller to realize the logic of the CLU to control the analog switches, generate time period *T1,* count time period *T2,* and do some mathematical computations followed by displaying the output as angle sensed (in degrees). The clock frequency was chosen to be 5 kHz. Figure 5.1 shows the snapshot of the experimental set up of LVDCAT along with integrator and comparator output on NI ELVIS Oscilloscope.

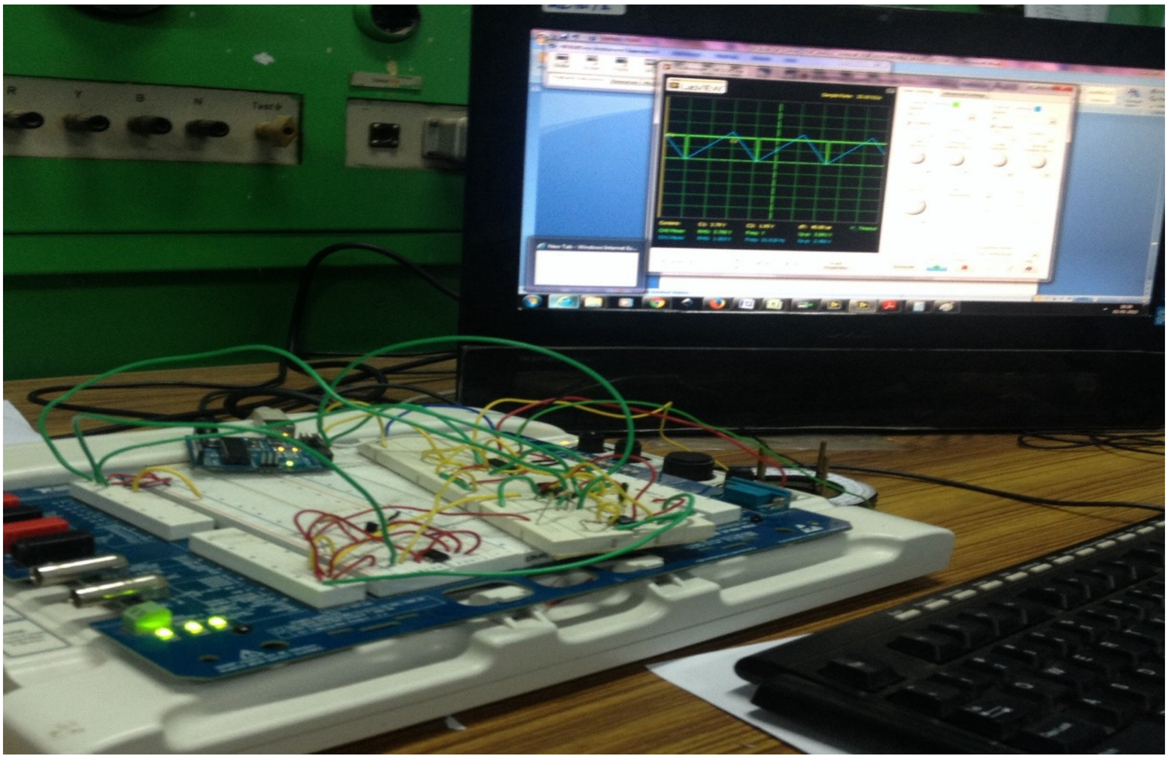

Figure 5.1: Experimental Setup of LVDCAT.

5.2 EXPERIMENTAL RESULTS

The integrator output and comparator output were observed on the NI ELVIS Oscilloscope with the variation of angle. The step decrease and increase in output of integrator is shown in figure 5.2(a) and 5.2(b).

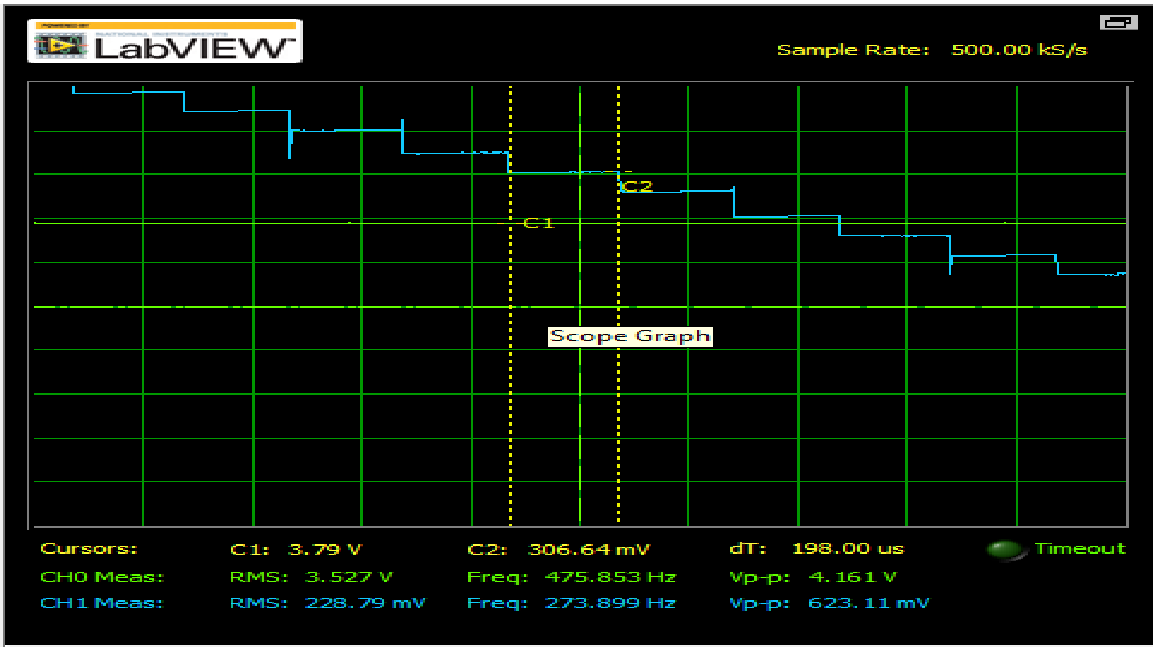

Figure 5.2(a): step decrease in output of integrator

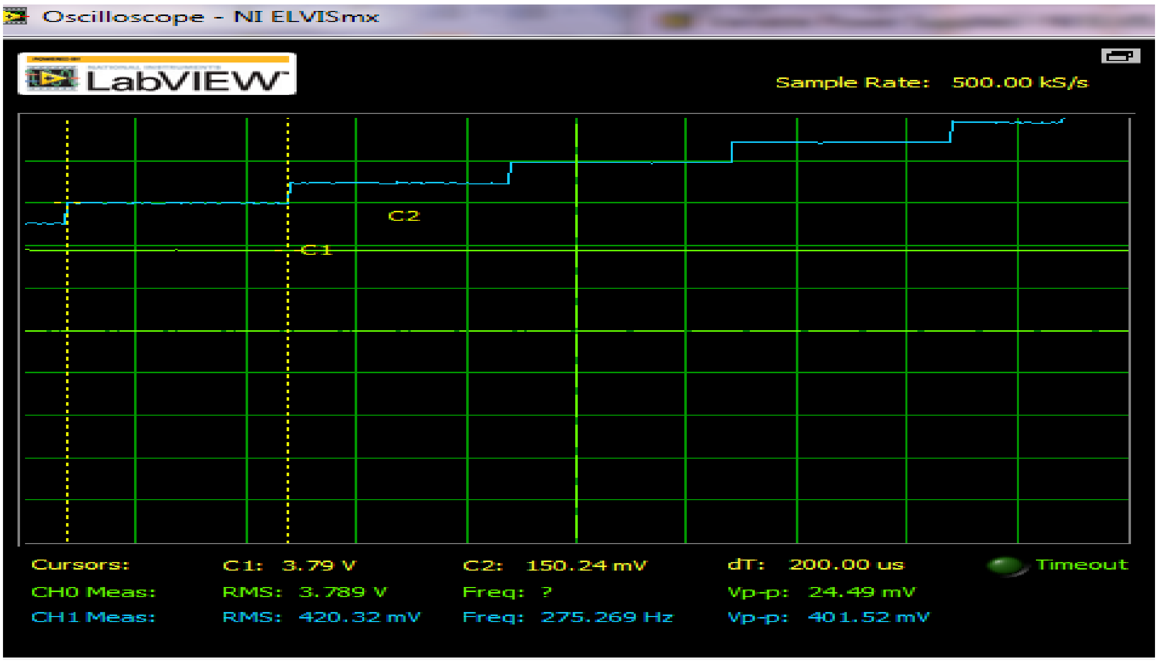

Figure 5.2(b): Step increase in output of integrator

It is observed from figure 5.2 that in each clock periode the output of the integrator is increased/ decreased with designed step size. The screenshots of the waveform of integrator and comparator output on oscilloscope of NI ELVIS II board are given in figure 5.3. It is seen from Figure 5.3 (a) that output of the integrator ramp in the positive direction for C1>C2.As expected, this condition was observed when angle was between 90 and 180 degree. The output of the integrator ramp in negative direction for C1<C2 as given in figure 5.3(b). As expected, this condition was observed when angle was between 0 and 90 degree The comparator output changes from High to low as expected in the first case and from low to high for C2>C1.This comparator output change is detected by the microcontroller and switches are controlled accordingly.

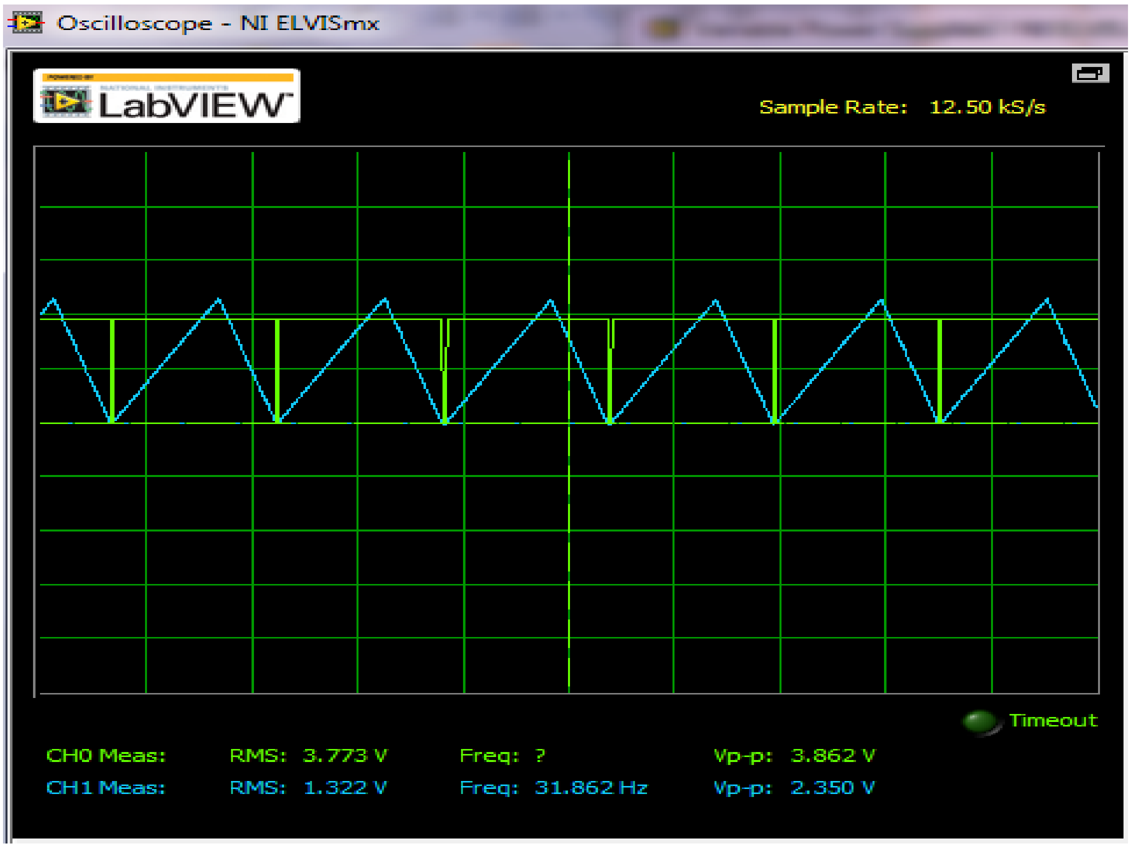

Figure 5.3 (a): Integrator and comparator output forC1>C2.

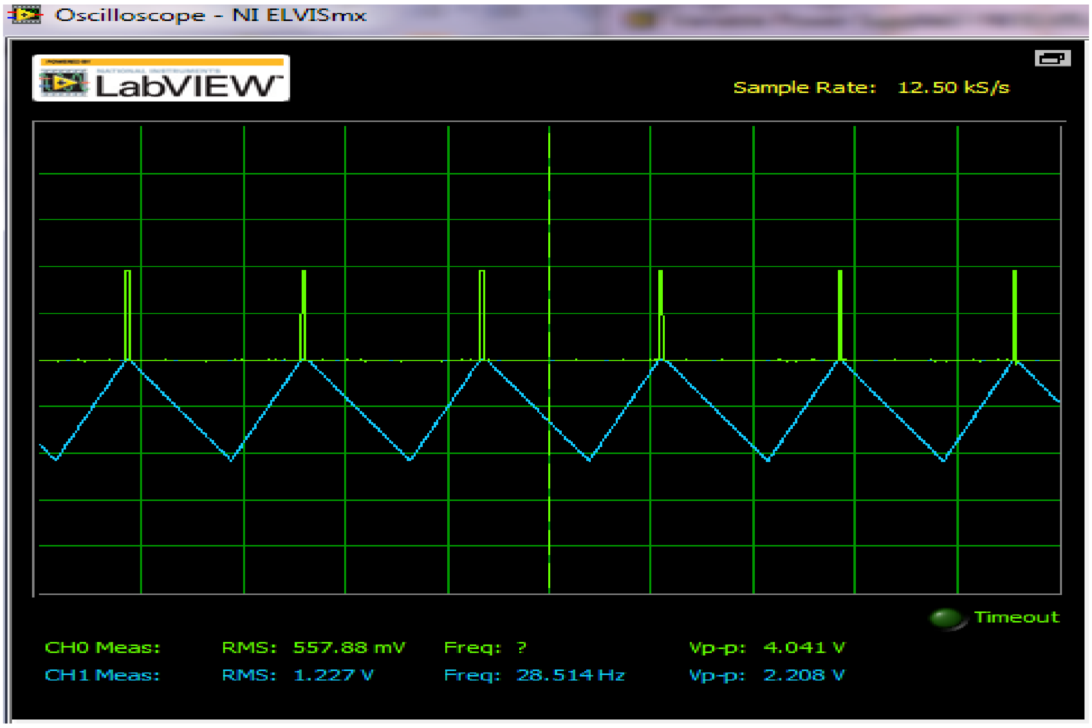

Figure 5.3 (b): Integrator and comparator output for C1<C2.

As discussed earlier the number of count (N2) varies with angular movement of the sensor. Angles were varied in steps of 10 degrees with the help of protractor image pasted on the plastic case. The values of N2/N1 corresponding to each angle were computed from Arduino software. The measured values of N2/N1 with the corresponding angles are tabulated in table 5.1.

Sl. No.	Angle(degrees)	$\left(\frac{C_1 - C_2}{C_1 + C_2}\right) = \frac{N_2}{N_1}$
1	0	-0.8113
2	10	-0.7717
3	20	-0.691
4	30	-0.6008
5	40	-0.5096
6	50	-0.4003
7	60	-0.3397
8	70	-0.2388
9	80	-0.1588

10	90.	-0.0772
11	100	0.0011
12	.110	0.0616
13	.120	0.1528
.14.	130	0.2236
15	140	0.3127
.16	150	0.3993
.17.	160	0.4735
18	170	0.544

Table 5.1: Value of N2/N1 at different angular positions.

From the values of Table 5.1 a graph was plotted showing the linear characteristics (Figure 5.4). The plot shown in Figure 5.4 resembles the ideal plot shown in Figure 2.4. The output varies linearly with changes in the angles as expected.

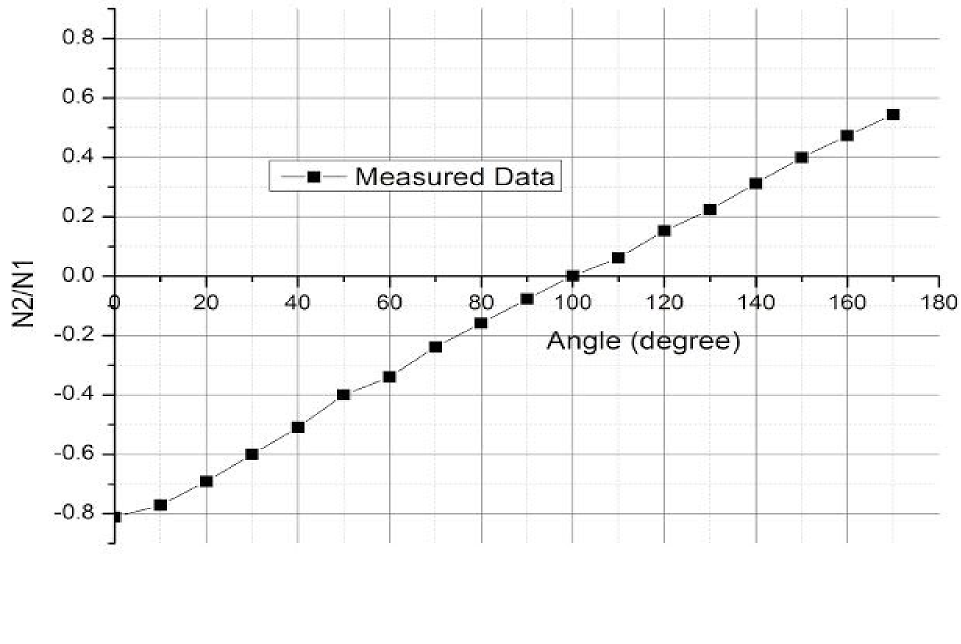

Figure 5.4: Linear variation of N2/N1 w.r.t Angle.

Further Linear fitting of data have been carried and found out percentage full scale error. The plot showing measured data, Linear fit and percentage full scale error is given in figure 5.5 and worst case error was found to be 3.84%. There was a slight lateral alignment issues around 90 degree due to imperfections in the washer used. This is the reason for maximum error around 90 degree.

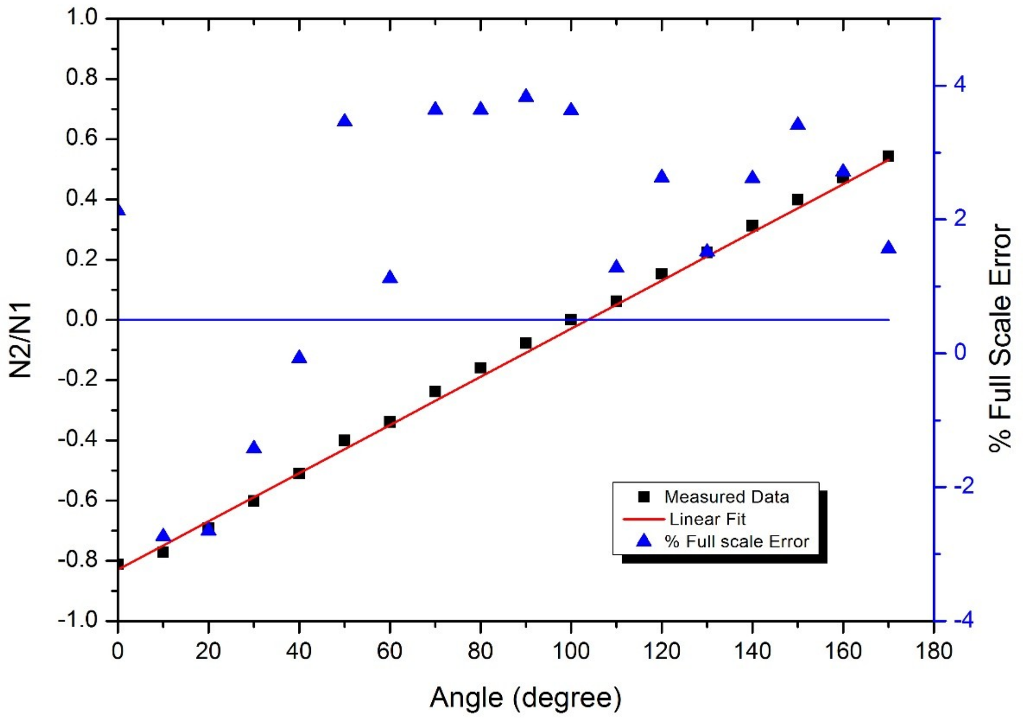

Figure 5.5: Linear fitting of measured data

CHAPTER 6: CONCLUSION AND FUTURE WORK

6.1 Conclusions

A Linear Variable Differential Capacitive Angular Transducer (LVDCAT) was successfully designed and fabricated for the purpose of applying in automobile brake system. The Angle sensor fabrication process was inexpensive which used only copper clad boards and ferric chloride as an etchant. The hardware testing was carried out in which signal conditioning circuit based on Dual Slope Capacitance to Digital Converter (DSCDC) was built on NI ELVIS board. An appropriate code was burnt in ATmega328 microcontroller for controlling switches used in the circuit. The angle sensed by the transducer was displayed on the serial monitor of Arduino Software and it was found to be varying linearly with the change in capacitance of the sensor.

6.2 Future Scope

Some additional improvements can be done in the work described in this thesis. Few of them are listed below:

- Signal conditioning circuit can be miniaturized and accommodated inside the angular sensor unit so as to use it in the actual scenario.

- The transducer can be made independent of the computer by using LCD display for displaying the angle sensed.

APPENDIX

Code used in ATmega328 Microcontroller

```
#include<avr/io.h>
 #include<avr/interrupt.h>
// Defining global variables
volatile uint8_t ovf0,ovf1; volatile unsigned int count=0;
int Comp =3; int pin =1;
Void statechange1() // function to display angle when Vc changes from High to low
 {
int count=TCNT1;
 // float abc=((count/39999.0));
 //Serial.println(abc,4); // can be used to display N2/N1
float temp=((count/342)+90);
Serial.println(temp);
count=0;
TCNT1 = 0; // reset counter
ovf1= 0;
ovf0= 0;
 }
Void statechange2() // function to display angle when Vc changes from low to high
 {
int count=TCNT1;
//float abc=((count/39999.0));
//Serial.println(abc,4);  // can be used to display N2/N1
float temp=(90-(count/326));
Serial.println(temp);
count=0;
TCNT1 = 0; // reset counter
ovf1= 0;
ovf0= 0;
 }
Void timer0_init()
```

```
{
  OCR0A= 200; //Defining count to obtain specified clock time periode
  TCCR0B |= (1 << CS01); // set up timer with prescaler = 8
  TCCR0A |= (1 << WGM01);
  TCNT0 = 0; // initialize counter
  TIMSK0 |= (1 << OCIE0A); // enable compare interrupt
  sei();  // enable global interrupts
}
Void timer1_init()
{
  OCR1A = 39999; //setting up preset integrating periode of 20ms.
 TCCR1B |= (1 << CS11)| (1 << WGM12);  // set up timer with prescaler = 8 and  enabling
CTC mode
 TCNT1 = 0;  // initialize counter
 TIMSK1 |= (1 << OCIE1A); // enable compare interrupt
sei();  // enable global interrupts
ovf1= 0;
}
// TIMER1 compare interrupt service routine and it is called whenever TCNT1 overflow ie
TCNT1 equal to OCR1A
ISR (TIMER1_COMPA_vect)
{
ovf1=ovf1^1;
}
// TIMER0 compare interrupt service routine and it is called whenever TCNT0 overflows ie
TCNTO equal to OCR0A
ISR(TIMER0_COMPA_vect)
{
ovf0=ovf0^1;
}
int main(Void)  //Main function to generate switching sequence to obtain a conversion cycle
{
Serial.begin(9600);
DDRD = 0b01110000;   // set input and output pins
```

```
 timer1_init(); // initializing Timer 1
timer0_init(); // initializing Timer 0
autozero(); //calling auto zero function
while(1)  // loop forever
{
if ((ovf1== 0)&(ovf0== 0))
          {
       PORTD =0b01010000;
          }
else if((ovf1== 0)&(ovf0== 1))
         {
       PORTD = 0b00100000;
         }
else if ((ovf1== 1)&(ovf0==0)&(digitalRead(Comp)==HIGH))
        {PORTD = 0b01100000;
           attachInterrupt(pin, statechange1, FALLING);
        }
else if ((ovf1== 1)&(ovf0== 1)&(digitalRead(Comp)==HIGH))
       {PORTD = 0b00010000;
           attachInterrupt(pin, statechange1, FALLING);
       }
else if ((ovf1== 1)&(ovf0== 0)&(digitalRead(Comp)==LOW))
       {PORTD = 0b01110000;
           attachInterrupt(pin, statechange2, RISING);
       }
else if ((ovf1== 1)&(ovf0== 1)&(digitalRead(Comp)==LOW))
       {PORTD = 0b00000000;
           attachInterrupt(pin, statechange2, RISING);
        }
  }
}

Voidautozero()  //Auto zero function
{
```

```
if (digitalRead(Comp)==HIGH)
   {
do
   {
   if (ovf0== 0)
   PORTD=0b01100000;
   if (ovf0== 1)
   PORTD=0b00010000;
   }
while(digitalRead(Comp)==HIGH);
  }
else
   {
do
   {
   if (ovf0== 0)
   PORTD=0b01110000;
   if (ovf0== 1)
   PORTD=0b00000000;
   }
while(digitalRead(Comp)==LOW);
   }
}
```

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