A LINEAR VARIABLE CAPACITIVE TRANSDUCER

FOR SENSING PLANAR ANGLES

SUBMITTED TO IITM

A THESIS

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CERTIFICATE

This is to certify that the thesis titled **A LINEAR VARIABLE CAPACITIVE TRANSDUCER FOR SENSING PLANAR ANGLES SUBMITTED TO IITM**, submitted by **R Venkitesh Chandran**, to the Indian Institute of Technology Madras, Chennai for the award of the degree of **Master of Technology**, is a bona fide record of the research work done by him under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

KEYWORDS: Angle Transducer, Relaxation oscillator, differential capacitance, signal conditioning

The linear variable differential capacitive angle transducer (LVDCT) is used to measure steering angle in an automobile. Steering-angle sensors (SAS) measure the steering wheel's actual position, the value which an increasing number of systems use to determine the direction the driver wants the vehicle to take.

A signal conditioning circuit suitable for push-pull type capacitive transducers is proposed. The circuit developed is capable of providing a linear output over the range of values between 0 to 180 deg as this is the maximum angle limit within which the steering wheel rotates. The push- pull type capacitive transducer which is designed becomes an integral part of a relaxation oscillator, the duty cycle ratio of the output of which becomes proportional to the measurand.

The prototype of the sensor is fabricated using three ferrous steel plates. Out of the three plates two plates are machined in a way that one increases in area as the other decreases over the range between zero and 180 deg producing a push-pull transducer. The hardware testing is done by implementing the signal conditioning circuit on the NI ELVIS board. LabVIEW software is used for implementing an indicator which helps in easy read out after doing appropriate mathematical calculations. The results obtained from conducting tests on the prototype indicate that the circuit possesses very low systematic errors.

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ABBREVIATIONS

LVDCT	Linear Variable Differential Capacitance Transducer
SAS	Steering Angle Sensor
ESC	Electronic Stability Control
EMI	Electro-Magnetic Interference
NI	National Instruments
ELVIS	Electronic Laboratory Virtual Instrumentation Suite
SPDT	Single Pole Double Throw
LabVIEW	Laboratory Virtual Instrumentation Electronic Workbench
LPF	Low Pass Filter
LCD	Liquid Crystal Display
VI	Virtual Instrument
ADC	Analog-to-digital converter
AI	Analog Input
DAQ	Data Acquisition

NOTATIONS

C	Capacitance
C_M	Maximum capacitance
C_1, C_2	Varying capacitance
d	Distance
A	Area
ε_0	Absolute permittivity
ε_r	Relative permittivity
θ	Measured Angle
V_o	Output Voltage
V_p	Positive reference voltage
V_N	Negative reference voltage
V_R	Reference voltage

CHAPTER 1 INTRODUCTION

1.1 TRANSDUCERS

An electronic instrumentation system consists of a number of components to perform a measurement and record its results. A generalized measurement system consists of an input device, a signal conditioning or processing device and an output device.

The input device receives the measurand or the quantity under measurement and delivers a proportional or analogous signal to the signal conditioning device where the signal is amplified, attenuated, filtered, modulated or otherwise modified in format acceptable to the output device.

The input quantity for most instrumentation system is a "*non-electrical quantity*". To use electrical methods and techniques for measurement, manipulation or control, the non-electrical quantity is generally converted into an electrical form by a device called '*transducer*'.

The transducer may be thought of as consisting of two important and closely related parts. These two parts are the sensing element (sensor) and the transduction element. 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, a resistive sensor or an inductive sensor depending on the application.

The sensors are to be embedded in the transducer to perform its intended function. The transduction element or a secondary element (a signal conditioning circuit) transforms physical variables into active signal such as changes in current or voltage. Figure 1.1 represents a possible arrangement of functional elements in an instrument and includes all the basic functions considered necessary for a description of any instrument.

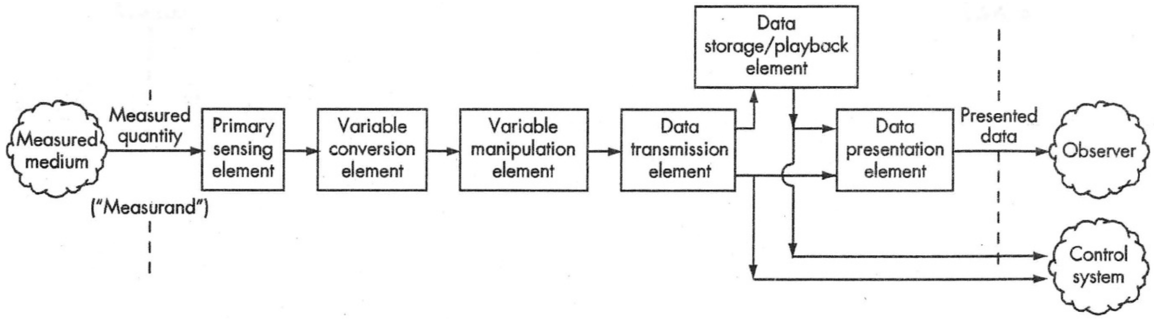


Figure 1.1: Functional elements of instrument or a measurement system.

Transducers are used in numerous applications in measuring/detecting various parameters occurring around us. They are of diverse nature and work on various principles. Based on the place of utilization as well as parameter to be measured their complexities vary as well as usefulness increases. With the main constraint as minimal power intake transducers designers these days are focused on this aspect so as to ensure high efficiency and minimal/no loading of the parameter being measured.

1.2 CAPACITIVE ANGULAR SENSOR IN STEERING ANGLE SENSORS:

Angle sensors are required in numerous applications in areas which include automobiles, industry automation and aerospace to name a few. There are a number of transducers which work on the principle of resistive, capacitive, inductive, magnetic, Hall-effect etc. these transducers mostly provide an output which is normally a varying voltage or a current. The 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. The LVDCT is an angular sensor for sensing steering angle based on capacitance transducer principle.

Steering-angle sensors(SAS) measure the steering wheel's actual position, the value which an increasing number of systems use to determine the direction the driver wants the vehicle to take. Measuring the position angle, rate of turn and force of the steering wheel is critical for Electronic Stability Control (ESC) systems. The SAS is located in a sensor cluster in the steering column. The cluster always has more than one steering position sensor for redundancy and to confirm data. The ESC module must receive two signals to confirm the steering wheel position. These signals are often out of phase with each other.

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 Transducer (LVDCT) which will sense the angular movement of a steering wheel and display the angle on a display unit. This angle sensor finds application in automobile SAS to sense the wheel's actual position. As the steering wheel is turned, the SAS produces a signal that oscillates between a positive and negative reference voltage. If we connect the common plate of our angle sensor to the steering wheel rod, the angular movement of this steering wheel can be sensed and hence the exact positon of wheel can be continuously monitored. Since the sensor is fabricated using ferrous steel plates it is an affordable sensor and also 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 LVDCT. Chapter 4 describes hardware set up used for the experiment. Chapter 5 provides experimental results of the designed LVDCT. 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 linear variable differential capacitive transducer (LVDCT) for measuring planar angles is one such device wherein the transducer uses the variation in capacitance, so as to find out the angular change. We know that capacitance is directly proportional to the area (A) and inversely proportional to the distance (d). By manipulating these two quantities we can vary the capacitance and further measuring the variation in capacitance can lead to a direct correlation between capacitance and the angle to be measured.

Capacitive transducers possess the inherent advantage of minimal power consumption, low sensitivity to temperature variations and no mechanical wear and tear. Also, shielding the sensor from stray electric fields is less complex. Capacitive sensor elements are used in many applications to measure parameters including displacement, proximity, humidity, acceleration, liquid level, gas concentration etc. They can be implement on printed circuit boards, glass substrates, silicon chips and other kinds of materials. Since the electrodes of the sensor do not need to be in mechanical contact with each other, they are suited for small-range contact-less sensing. The main drawback of the sensor is the contamination and 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 the capacitor is given by

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d} \tag{2.1}$$

where C is the capacitance of the capacitor ε_0 is the absolute permittivity, ε_r is the relative permittivity, A is the area overlapped by the plates and d is the distance between the parallel plates. It can be seen from the above relation that the capacitance of a capacitive transducer can depend on the area of the plates (A), the distance between the plates (d) and the dielectric constant of the material used between the plates.

In the instruments using capacitance transducers, the value of 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. 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 dielectric 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 the 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 is calibrated against the input quantity, which is displacement. This principle can also be extended to measure pressure, velocity, acceleration etc.

2.3 DIFFERENTIAL TYPE CAPACITIVE TRANSDUCERS

Capacitive transducers are based on a change in capacitance in response to changes in the physical input. The applications of these transducers are varied and diverse – from humidity and moisture measurements to the sensing of pressure [1], [2].

Sensitivity of these types of transducers can be doubled and some of the non-linearity eliminated by the use of the differential configuration (or the push-pull type, as they are more popularly called) [3]. In some versions, the central plate, in a three parallel-plate arrangement, moves in response to the variations of the physical input keeping the outer plates fixed. It is also possible to construct capacitive transducers wherein the central plate is fixed and the outer plates move. The equivalent circuit representation of such a transducer is given in Fig. 2.1.

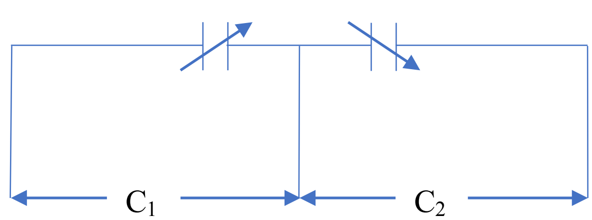


Fig 2.1 Equivalent circuit for a differential capacitor

C_1 and C_2 can be expressed as:

$$C1 = \frac{\epsilon_0 \epsilon_r A}{d(1 \pm \frac{\Delta d}{d})} \qquad C2 = \frac{\epsilon_0 \epsilon_r A}{d(1 \mp \frac{\Delta d}{d})} \qquad (2.2)$$

where Δd is the displacement of the capacitor plate(s) from the nominal distance d between them, ε_o is the permittivity of free space, ε_r is the relative permittivity of the dielectric between the plates and A is the area of the plates.

In general, for a positive displacement x, we can represent C_1 and C_2 as

$$C_1 = \frac{1}{(1-kx)} \qquad C_2 = \frac{1}{(1+kx)} \qquad (2.3)$$

k being a constant. Alternately, the displacement can be sensed by varying the surface area of the electrodes of the capacitor(s) in proportion to the displacement. The output of such a transducer will be linear with respect to the input. The capacitances of a push-pull type sensor can then be expressed as

$$C_1 = C(1-kx) \qquad C_2 = C(1+kx) \qquad (2.4)$$

2.4 LINEAR VARIABLE DIFFERENTIAL CAPACITIVE TRANSDUCER (LVDCT)

The sensor part of the proposed LVDCT is as shown in Fig 2.2. The sensor consists of three plates. A common plate with a fixed area acts as one plate for the capacitors C_1 and C_2 (Fig 2.2(b)). As seen from the figure the two spokes protruding out of the circular part which are 180deg apart constitute the effective area of the top plate. The other two plates are realised in a semi-circular fashion (Figure 2.2(a)) such that as one moves from 0 to 180 deg, the area of one of the plate increases and the other plate decreases. They vary in such a fashion that their total area remains the same at all times. It is to be noted that inner semicircles are shorted together. Also, the outer two plates are shorted together.

The complete plate setup is mounted on to a glass which can move in a circular fashion about the centre. The top plate (with fixed area) and the bottom plates are mounted in such a fashion that as the top plate moves from 0 to 180deg the two bottom plates which vary in area are exactly beneath the top plates, hence ensuring that the total area remains same at all times. In the prototype that was developed the two bottom plates where fixed

Figure 2.2 (a): Bottom plates

Figure 2.2 (b): Top (common) plate

Figure 2.2 Sensor part of the proposed LVDCT

with the top plate having the freedom to rotate. The two plates are separated by a thin sheet of polyethylene which acts as the dielectric for the capacitors C_1 and C_2.

Mathematically the variation of C_1 and C_2 in terms of angle (θ) can be expressed as:

$$C_1 = \frac{C_M \theta}{180}$$

$$C_2 = C_M(1 - \frac{\theta}{180}) \quad (2.5)$$

So now if we define a function $f(C_1, C_2) = \left(\frac{C_1 - C_2}{C_1 + C_2}\right)$

It nicely turns out that $f(C_1, C_2) = (\frac{2\theta}{180} - 1)$ if θ is measured in degrees

$= (\frac{2\,\theta}{\pi} - 1)$ if θ is measured in radians

Graphical representation of equation 2.5 is as shown in Figure 2.3. It is easily seen from the figure that the value of capacitance C_1 increases from C_0 to C_M in the interval $0° < \theta < 180°$. At the same time the value of C_2 decreases from C_M to C_0 where C_M is the maximum capacitance and C_0 is the minimum capacitance. If the difference of the two capacitances $(C_1 - C_2)$ is divided by the total of the capacitance $(C_1 + C_2)$ it gives us a linear plot.

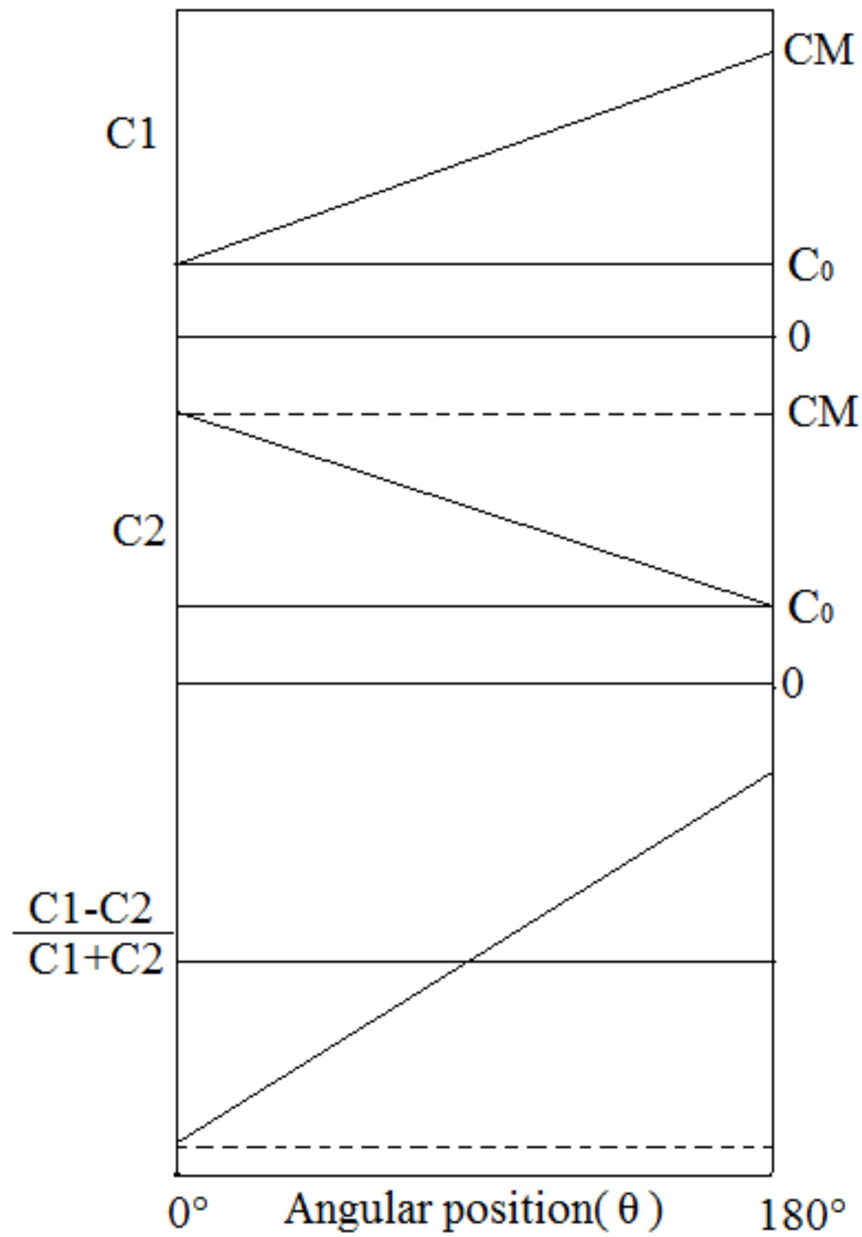


Figure 2.3: Variation of C_1, C_2 and $f(C_1, C_2)$ wrt θ

2.5 SENSOR FABRICATION

The sensor is fabricated using ferrous steel plates which are mounted on glass and further concentrically stacked on top with a spindle in the center as shown in figure 2.4. The bottom plate is fixed and does not move. The two-differential semicircular ferrous steel plates are placed on the fixed bottom glass in such a fashion wherein the area of one plate increases proportionally as the area of the other plate decreases. The top glass plate which holds the common plate is rotatable with respect to the spindle and the common plate moves over the differential plates to create capacitance C_1 and C_2. Hence as the overlapping area varies the capacitance C_1 and C_2 varies proportionally. A polyethylene sheet is used as a dielectric and is placed in between the plates.

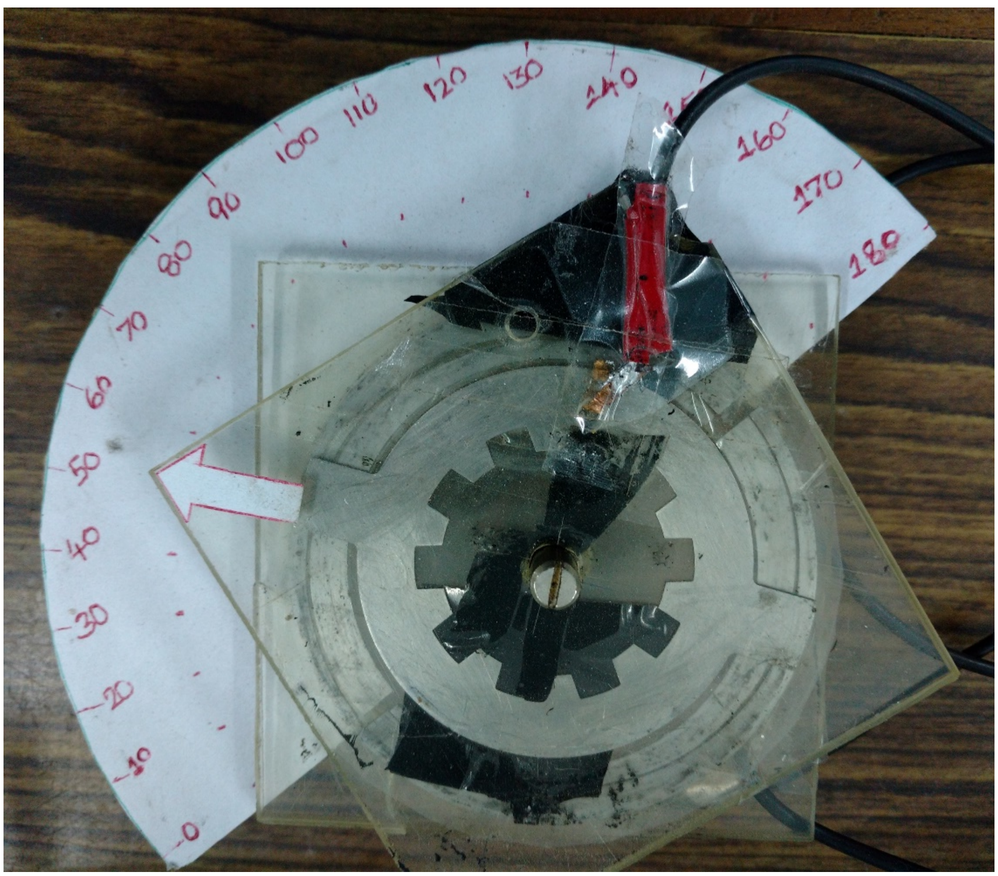


Figure 2.4: Fabricated sensor

The specifications of the sensor are as follows:

Electrode material	Ferrous steel
Insulator	Polyethylene
Electrode thickness	0.72mm
Insulator thickness	0.12mm
Dielectric constant of Polyethylene	2.25
Inner radius	55.67mm
Outer radius	71.91mm

Table 2.1: Specifications of the sensor

2.6 CHALLENGES FACED DURING SENSOR FABRICATION

During the fabrication of the sensor many challenges were observed, including precision machining of the mountings and alignment of steel plates to form the capacitor. The main challenges/issues faced are as follows:

a Soldering of lead wires on to ferrous steel:

The lead wires are required to have a good/strong connection with the plates. The best solution to have a good electrical connection is to solder the lead wires on to plates. However, the solder was not getting adhered to the ferrous steel.

Solution: The connection from the electrodes was taken using copper strips which were soldered on to the electrodes. To increase the adhesion of solder on to the plates the area was thoroughly cleaned. Further flux was used to improve the adhesiveness and improve the strength of the bond. The other end of the copper strip was soldered to the lead wire. The entire soldered portion was fixed on to the glass plate using tape, so as to ensure minimal strain on the joints.

The lead wires are used to complete the circuit from the electrodes to the capacitor plates

b. Variations in capacitance due to undulations of the plate surface

The capacitance is a function of distance between the plates. For the sensor to function as expected the distance between the common plate and the other two bottom plates need to be equal. However due to uneven mounting surfaces the distance between top plate and the bottom plates were different resulting in different capacitance values.

Solution Initially the bottom plates where on a base of plastic. However due to repeated removal and sticking of the plates the adhesive formed lumps underneath the plates creating undulations when stuck again and again. Hence the entire setup was moved on to a glass plate with an assured flat surface. This ensured minimal variations in distance between the plates which led to a better result.

c. The capacitance value formed by the plates were very small

The value of the capacitance formed by the plates were very small from 6 to 16pF

Solution: An exact replica of the semicircular bottom plates was fixed so as to form a full circle. The protruding part on the top plate which was 180 deg opposite to the other plate helped in forming a capacitor. This ensured doubling of the capacitance value and it now varied from 12 to 32pF.

CHAPTER 3: SIGNAL CONDITIONING CIRCUIT

3.1 INTRODUCTION

The information or data generated by a basic measuring device generally require "processing" or "conditioning" of one sort or another before they are presented to the observer as an indication or a record.

To obtain a measurable output relative to the parameter being sensed by a capacitive sensor, a signal conditioning circuit that converts the variations in the sensor capacitance C_1 and C_2 to a proportional analog voltage is required [2]. An accurate and linear representation of the measured quantity can be obtained ratio metrically - by dividing the difference in capacitances of the two capacitors by their sum.

3.2 RELAXATION OSCILLATOR CIRCUIT:

A circuit based on novel relaxation oscillator based signal conditioning circuit for push-pull kind of capacitive transducers, where the transducer itself forms a part of the oscillator is used. This circuit exhibits several advantages, such as increased linearity and accuracy [4].

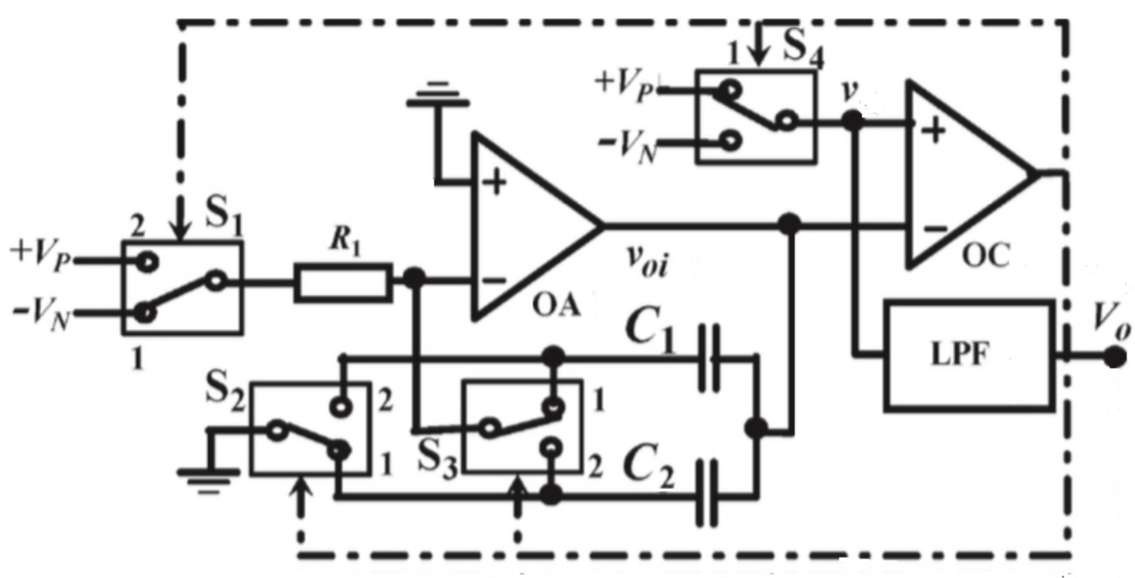


Figure 3.1 Signal Conditioning Circuit

Switches S_1, S_2, S_3 and S_4 are controlled by output of the comparator OC and hence simultaneously changes state. Initially let all the switch be at position 1. Then capacitor C_1 is in the feedback path of Opamp OA and C_2 becomes load on the output of OA. Hence at any given instant voltage across C_1 will be equal to C_2.

OA with capacitor C_1 in feedback and R_1 in input becomes an integrator. S_1 is in position 1, the voltage connected to this integrator is $-V_n$ and hence the output voltage V_{oi} increase in positive direction with a slope of V_n/R_1C_1. V_{oi} reaches $+V_p$. As V_{oi} reaches $+V_p$ say after T_H, comparator OC changes state, forcing S_1, S_2, S_3 and S_4 to position 2. In this condition C_2 comes in the feedback path of OA and C_1 is connected to the ground. Since S_1 is now in position 2 $+V_p$ is connected to input of the integrator and its output V_{oi} gradually decrease with a slope $-V_p/R_1C_2$ until it reaches $-V_n$. After time T_L comparator OC reverts to its earlier state and sets all switches S_1, S_2, S_3 and S_4 to position 1.

The circuit goes into oscillations at frequency

$$f = \frac{1}{T} = \frac{1}{(T_H + T_L)}$$

$$T_H = 2R_1C_1 \qquad T_L = 2R_1C_2 \tag{3.1}$$

The output of S_4 is fed to Low Pass Filter (LPF). Now if we choose $V_p = V_N = V_R$ and cut off frequency to be very low compared with the frequency of oscillation f. then output of the filter is

$$V_o = \frac{1}{T}\left[\int_0^{T_H} V_R\, dt - \int_{T_H}^{T} V_R dt\right]$$

$$= \frac{V_R}{T}\left[[T_H] - [T - T_H]\right]$$

$$= V_R\left[\frac{T_H - T_L}{T_H + T_L}\right]$$

Substituting the values of

$$T_H = 2R_1C_1 \qquad T_L = 2R_1C_2$$

$$V_o = V_R[\frac{C_1 - C_2}{C_1 + C_2}] \tag{3.2}$$

Now substituting the values of C_1 and C_2 from equation 2.5

We have $$V_o = V_R\left[\frac{2\,\theta}{180} - 1\right]$$

3.3 DATA PRESENTATION ELEMENT

The output of the Low Pass Filter is a voltage V_o which varies from $-V_N$ to $+V_p$. This voltage can be observed on an oscilloscope and the output can be calibrated so as to read out the values of input angle. In order to make this data presentable and meaningful NI LabVIEW was used for acquiring and displaying the signals in the desired manner

3.4 DATA ACQUISITION WITH LabVIEW

The ability to pull in data from an outside *source*, process the data, and send signals back out to control devices is what sets LabVIEW apart from numerous other software products that can be used to analyse data. The goal of *data acquisition* is to capture data from one or more laboratory instruments on a computer so that it can be analysed, stored and displayed.

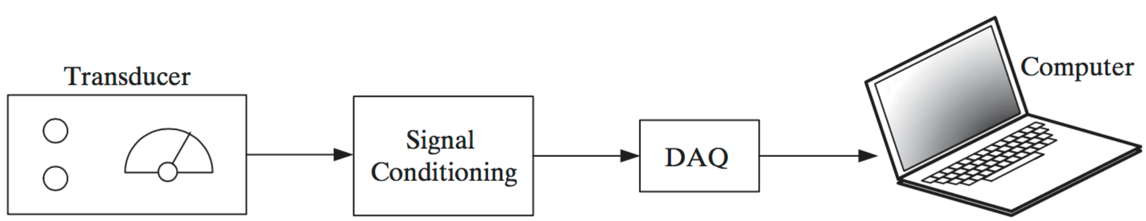
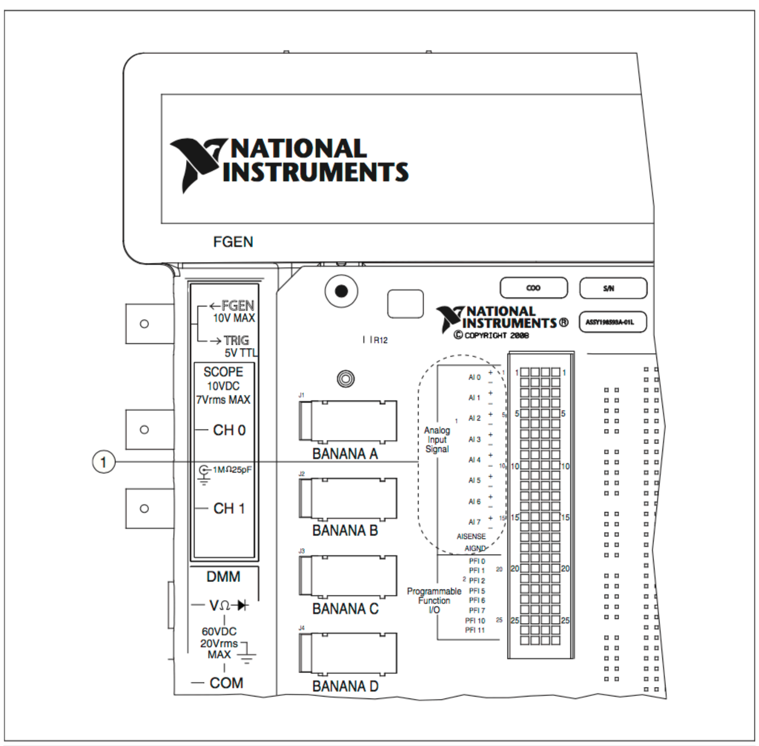


Figure 3.2: Data acquisition system with external signal conditioning. [12]

After the required signal conditioning, which helps to adjust the signal type and range of the output signal to align with the requirements of the data acquisition system, data can be collected. The computer driving the data acquisition system will need to know what signal(s) to measure,   how often to take readings and how many readings to collect, or how long to continue reading the signal(s)

The data acquisition process is configured by providing this required information prior to collecting data. The LabVIEW approach is to create a data acquisition *task* that contains this information. The collected data is available to the computer system and can be displayed, modified, analysed, or simply stored.

The heart of most data acquisition systems is an analog-to-digital converter (ADC) that can receive an analog signal and convert it to a digital form that can be used and stored on a computer system. The sensor's analog signals are connected to an analog input (AI) as shown in figure 3.3. Many data acquisition systems provide several AIs (called *channels*) that share a single ADC by means of a multiplexer.



1 Analog Input Connections

Figure 3.3 Analog Input connections on prototyping board [12] [13]

The LabVIEW operates the data acquisition system and a request for a data acquisition device to collect one or more data values is called a *task*. Once we define a data acquisition task, the following questions are to be answered. The questions include which data acquisition device will be used, which AI channel(s) will be used, how often will each channel be sampled and how many samples should be collected?

This task can be defined from inside LabVIEW using the DAQ Assistant VI or from outside of LabVIEW using National Instruments Measurement and Automation Explorer.

The task for data acquisition was created in LabVIEW. The block diagram for the display task created is as shown in figure 3.4. The corresponding front panel which was made as shown in figure 3.5

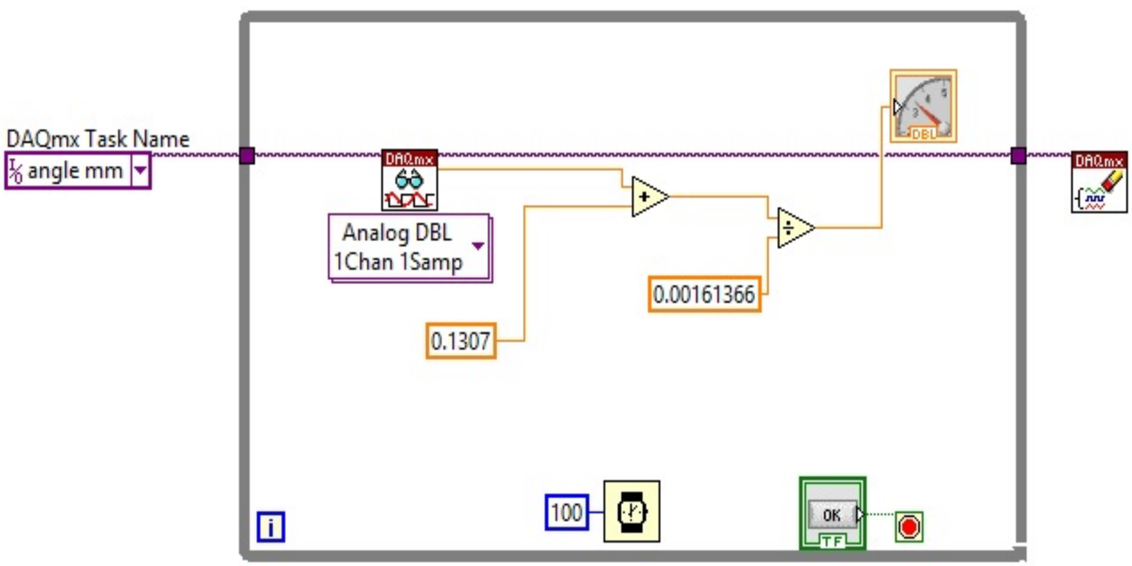


Figure 3.4 Block diagram for display

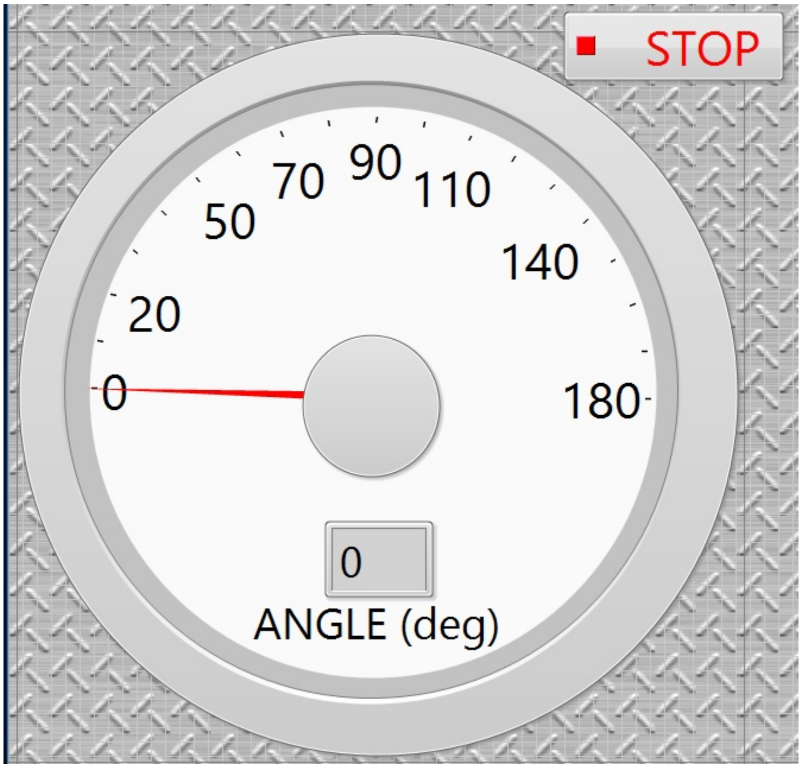


Figure 3.5 Front panel

In order to get the linearized output, the data obtained from the readings of different angles was collated and was plotted with respect to the angle. This plot was linear fitted using MATLAB and the values of coefficients were noted. This procedure was carried out a number of times and the average values of the coefficients was used in the block diagram

CHAPTER 4: HARDWARE SETUP FOR THE EXPERIMENT

4.1 INTRODUCTION

The approach adopted in sensing/ measuring the angle is represented in the form of a block diagram in Figure 4.1. The angle sensor creates the differential capacitance as discussed in Chapter 2. The signal conditioning circuit was built on National Instruments Educational Laboratory Virtual Instrumentation Suite II (NI ELVIS II), manufactured by National Instruments. The sensor forms an integral part of the signal conditioning circuit and a comparator was used to control the SPDT switches. Further the Laboratory Virtual Instrumentation Electronic Workbench (LabVIEW) is used to display the reading on a Virtual Instrument (VI). This chapter describes in detail about the hardware setup such as NI ELVIS II, LF 347 and MAX 4708EPE MUX.

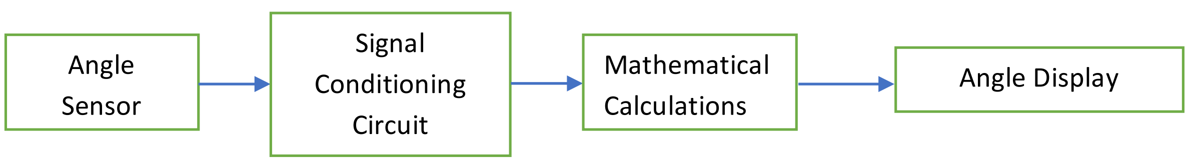


Figure 4.1 Block Diagram

4.2 NI ELVIS II

The NI Educational Laboratory Virtual Instrumentation Suite (NI ELVIS) is a hands-on design and prototyping platform that integrates 12 of the most commonly used instruments – including the oscilloscope, DMM, function generator, and Bode analyzer – into a compact form factor ideal for the hardware lab or classroom [12] [13].

The NI ELVIS II Workstation can be controlled either via manual dials on the stations front or through software virtual instruments. The NI ELVIS 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

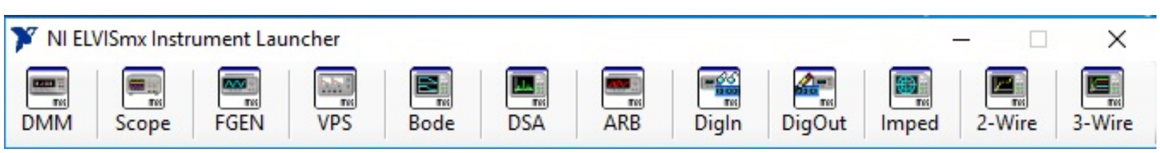


Figure 4.3 NI ELVISmx Instrument Launcher

4.2.1 NI ELVIS II Hardware

The NI ELVIS II hardware consists of a **Workstation** and **Prototyping Board**

Workstation: The workstation consists of a top, rear and a bottom panel. The top panel provides easy to operate knobs for variable power supplies and function generator on the right side as can be seen on the right side of NI ELVIS II Hardware (Fig 4.2). It also offers convenient connectivity and functionality in the form of BNC and banana-style connectors to the function generator, scope, and DMM instruments. This can be seen arranged on the left side of the board.

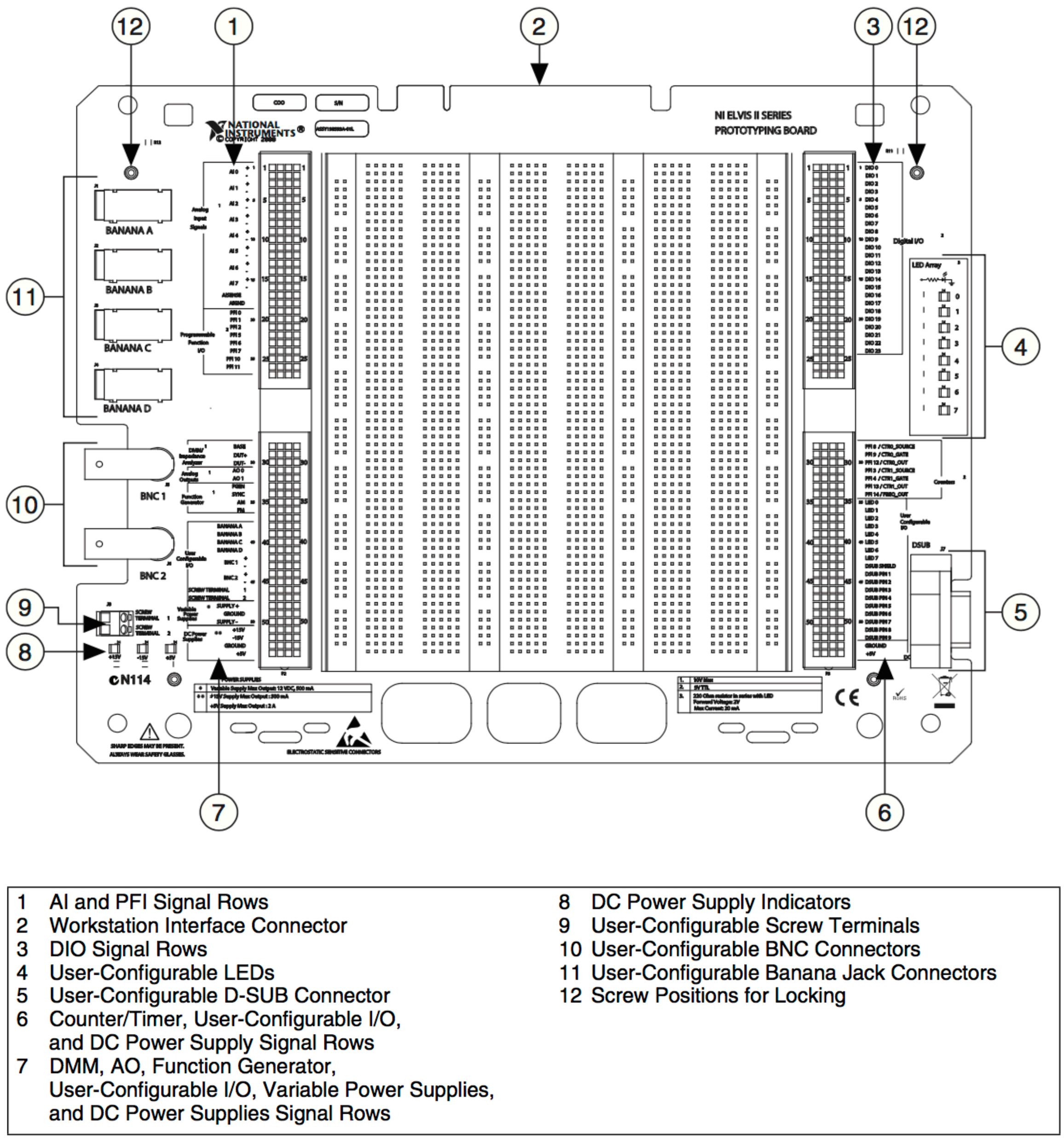


Figure 4.4 Prototyping Board

Prototyping Board: The NI ELVIS II Series Prototyping Board connects to the workstation (Fig 4.4). It provides an area for building electronic circuitry and has the necessary connections to access signals for common applications. You can use multiple prototyping boards interchangeably with the workstation.

4.2.2 NI ELVIS II Software

The NI ELVISmx software is created in LabVIEW, takes the 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:

Arbitrary Waveform Generator(ARB): This advanced-level SFP instrument uses the AO capabilities of the device to create a variety of signal types using the Waveform Editor software, which is included with the NI ELVISmx software.

Bode Analyzer(Bode): A full-function Bode Analyzer is available with NI ELVISmx which combines the frequency sweep feature of the function generator and the AI capability of the device. One can set the frequency range of the instrument and choose between linear and logarithmic display scales.

Digital Reader (DigIn) and Writer(DigOut) The digital reader reads digital data from the NI ELVIS II Series digital lines. The digital writer updates the NI ELVIS II Series digital lines with user-specified digital patterns.

Digital Multimeter(DMM): This commonly used instrument can perform measurements which include Voltage (DC and AC), Current (DC and AC), Resistance, Capacitance, Inductance, Diode test and Audible continuity. It can also measure the capacitance and inductance using the Impedance analyser.

Digital Signal Analyser(DSA): The DSA performs a frequency domain transform of the AI or scope waveform measurement and can either continuously make measurements or make a single scan. It can also apply various window and filtering options to the signal.

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

Impedance Analyser(Imped): This instrument is a basic impedance analyser that is capable of measuring the resistance and reactance for passive two-wire elements at a given frequency.

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

Two-wire (2 wire) and Three-wire (3 Wire) Current-Voltage analysers: These instruments can be used to conduct diode and transistor parametric testing and view current-voltage curves.

Variable Power Supplies(VPS): With these SFP instruments, the negative power supply can output between –12 and 0 V, and the positive power supply can output between 0 and +12 V.

4.3 LabVIEW

LabVIEW [14] is a graphical programming language that was developed to make it easier to collect data from laboratory instruments using data acquisition systems. It is easy to use as it has wiring connectors to write your computer programs. LabVIEW can perform the following functions.

• acquire data from instruments

• process data (e.g. Filtering, transforms)

• analyse data

• control instruments and equipment

4.3.1 LabVIEW VI

LabVIEW programs are called VIs. Originally, VI stood for *virtual instrument*, but LabVIEW is now used for many more applications than just creating a computer simulation of an instrument, and LabVIEW programs are typically referred to simply as VIs. A LabVIEW VI has two parts:

- **Block Diagram**: Holds the programming elements (called *blocks*, *functions*, or sometimes *subVIs*) that are wired together to build the graphical program. The block diagram used in this project is shown in Figure 3.4.
- **Front Panel**: It displays the controls (knobs, buttons, graphs, etc.) and represents the graphical interface for the VI. Figure 3.5 shows a front panel in LabVIEW VI.

4.3.2 LabVIEW Functions

A LabVIEW function is a piece of program code that works as a unit. There are many math functions in LabVIEW, including Basic Math Functions such as Add, Subtract, Multiply, Divide, Increment, Decrement, Absolute Value, Square, Square Root Reciprocal Trig and Hyperbolic Trig Functions, Log and Exponential Functions, Matrix Functions, Optimization Functions and Differential Equations Functions. These Functions typically accept one or more values as inputs and return a result. Since LabVIEW is a graphical programming language, the functions are placed on the block diagram as nodes. As an example, the node for the **Add** function is illustrated in Figure 4.5. The Add function requires two inputs (the values to be added) and has one output (the sum).

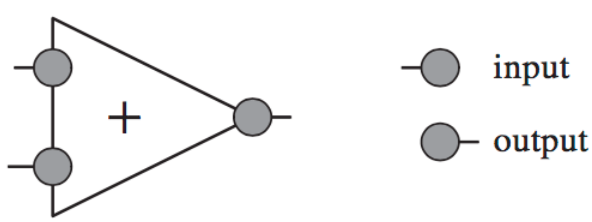


Figure 4.5: The ADD Function node showing terminals

The nodes for math functions have terminals for inputs (required values) and outputs (results). The function nodes are wired to control nodes and indicator nodes to create the LabVIEW program.

4.4 SIGNAL FLOW

Using the hardware's as explained in the above sections the block diagram of figure 4.1 was realised. The LF 347 IC was used as op amp which functioned as the integrator and comparator in the relaxation oscillator. The LF347 is a low cost, high speed quad JFET input operational amplifier with an internally trimmed input offset voltage [10]. The SPDT switches S_1, S_2, S_3 and S_4 in the relaxation oscillator were implemented using MAX4708 8:1 multiplexer IC [11].

The different blocks were interfaced with each other so as to ensure smooth signal flow. MATLAB was used for mathematical calculations which were involved in fine tuning the output for display.

CHAPTER 5: EXPERIMENTAL SETUP AND RESULTS

5.1 INTRODUCTION

In order to demonstrate the practical functioning of the proposed transducer, a prototype unit was built on the NI ELVIS II board and tested. The angle sensor constructed was used to provide the capacitance C_1 and C_2. A precision voltage V_R was provided by a DC supply source.

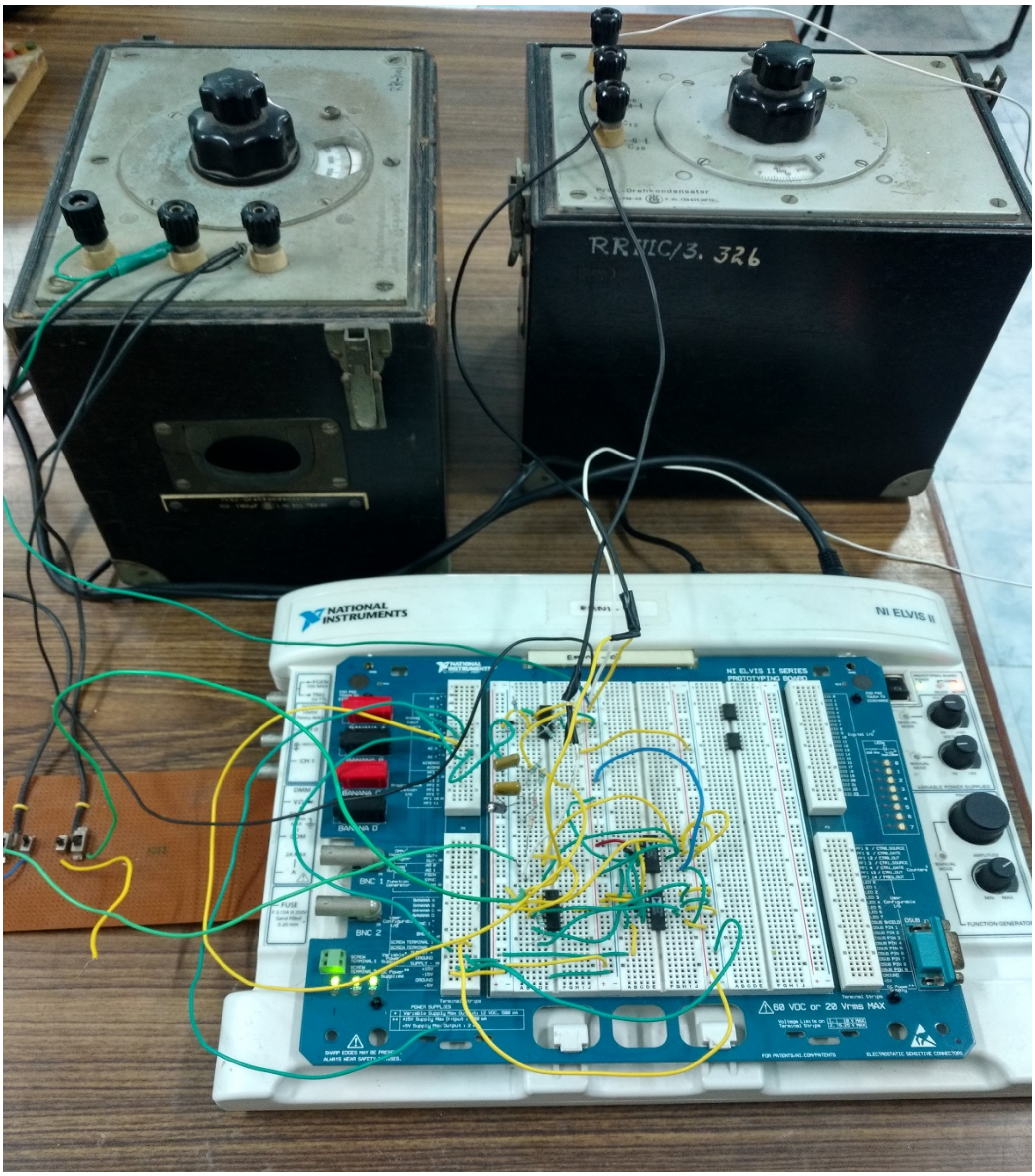


Figure 5.1: Experimental Setup of LVDCT

The entire circuit can be divided into a relaxation oscillator and a Low Pass Filter. To realise the relaxation oscillator, we require an Integrator and a comparator. Both these sub circuits use op amps as their heart and LF347 manufactured by Texas Instruments was used for realising them. MAX4708 ICs manufactured by Maxim Integrated was used to realise the switches S_1, S_2, S_3 and S_4. The supply voltage for both the ICs were provided from the ELVIS board. Further the LPF was realised using RC circuit.

5.2 EXPERIMENTAL RESULTS

The integrator output and the output of Switch S_4 were observed on the NI ELVIS oscilloscope with variation in angle. Initially the circuit was tested using standard capacitance boxes which were able to provide differential capacitance as seen in figure 5.1. Further the sensor was introduced into the circuit and the waveforms were observed. The output of integrator and switch S_4 were observed.

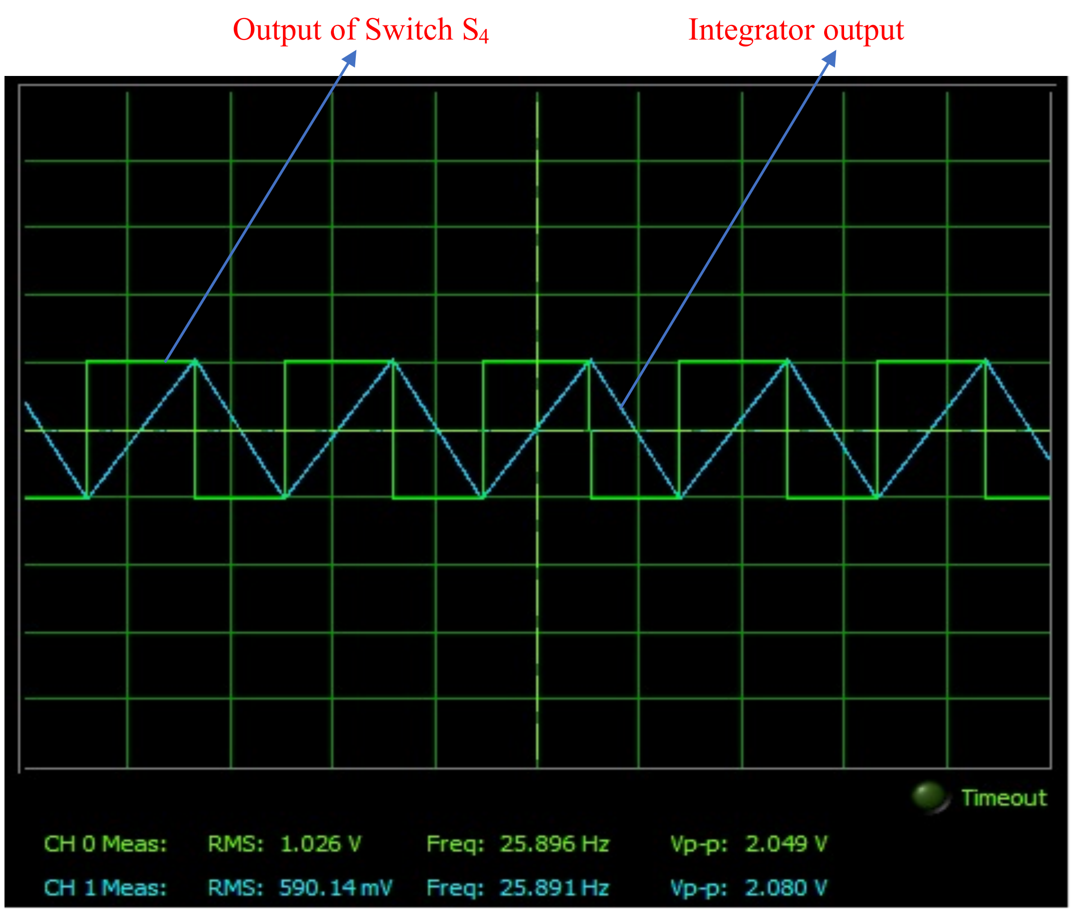


Figure 5.2: Output of Integrator and Switch S_4

The waveform (blue) indicates the ramping up and down of the integrator with the reference voltage of $+V_p$ and $-V_N$. At the same time the output of Switch S_4 (green) also varies between $+V_p$ and $-V_n$.

Sl No	Angle (degrees)	Output Voltage (V_o)
1	10	-0.229
2	20	-0.193
3	30	-0.163
4	40	-0.118
5	50	-0.084
6	60	-0.072
7	70	-0.052
8	80	-0.03
9	90	0.004
10	100	0.016
11	110	0.051
12	120	0.063
13	130	0.084
14	140	0.117
15	150	0.127
16	160	0.19
17	170	0.242

Table 5.1. Value of V_o at different angles

Now the output of the Switch S_4 is provided to a LPF. As we have chosen $V_p = V_N$

= V_R and the cut off frequency f_c of the LPF to be very low compared with the frequency of oscillation f_o we can get a steady voltage at the output of the filter which is proportional to differential ratio $(\frac{C_1 - C_2}{C_1 + C_2})$. The measured values of angle wrt the output of LPF is given in Table 5.1

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.

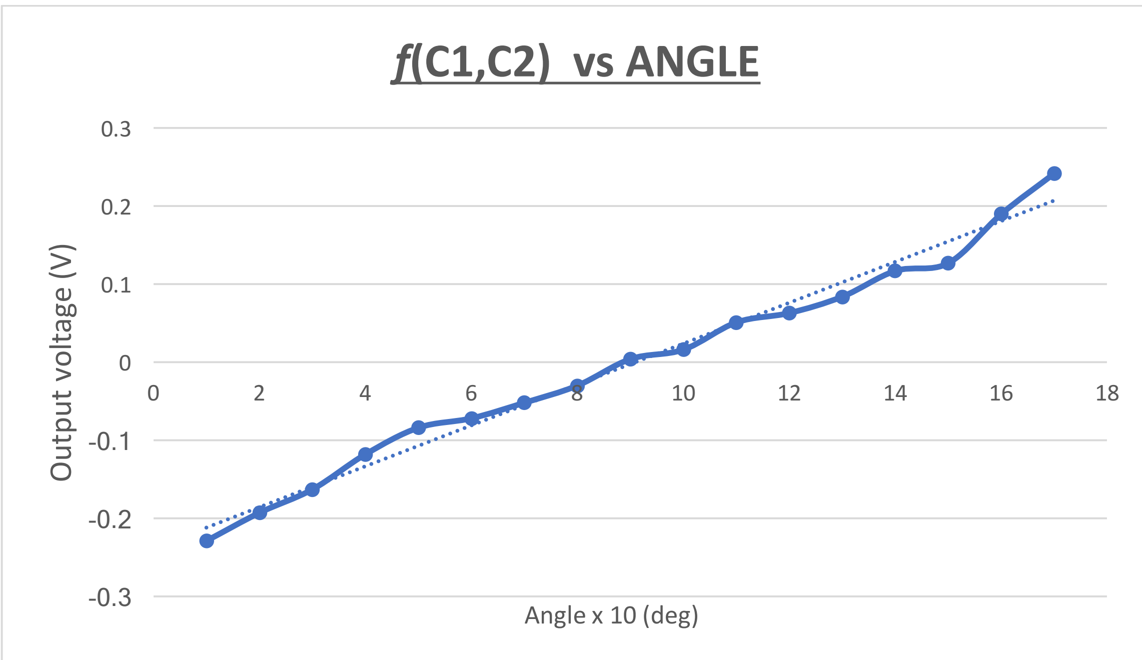


Figure 5.3 Linear variation of V_0 wrt angle

Further linear fitting of the data was carried out and the full-scale percentage error was found out.

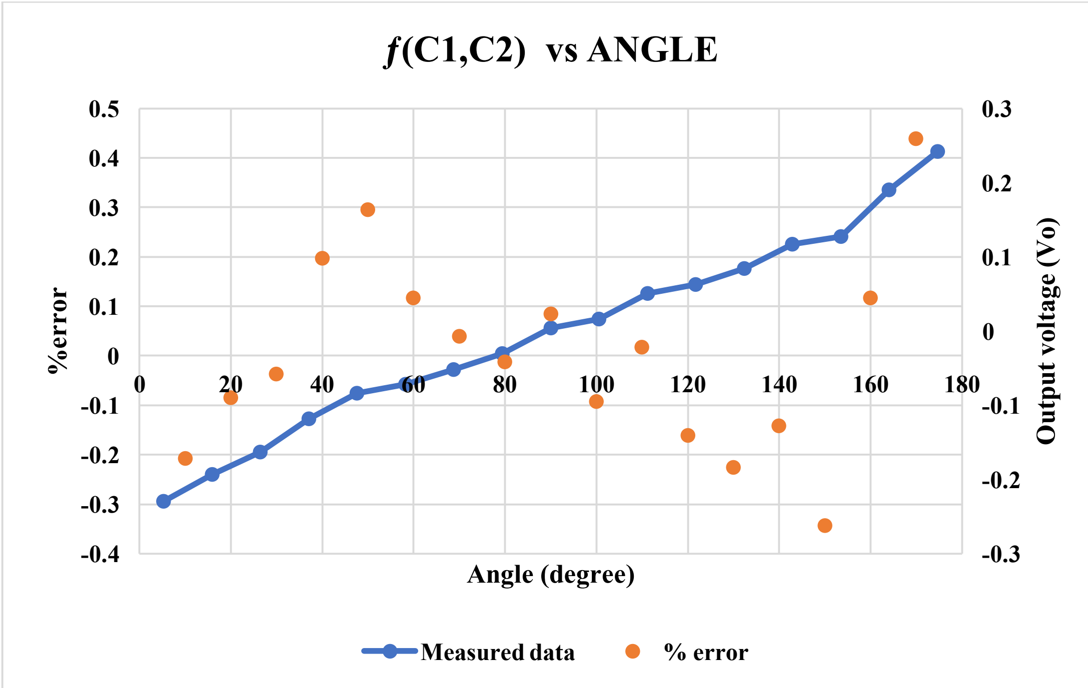


Figure 5.4: Measured data and % error

The plot showing the measured data and full-scale percentage error is shown in Figure 5.4. It is seen that the maximum full scale percentage error was 0.43%. As seen from the table the measurements have been taken from an angle of 10 degree to an angle of 170 degree. This is because of the construction of the sensor as top plate is symmetrical in construction and covers an equal area on either side at 0 and 180 deg.

CHAPTER 6: CONCLUSION AND FUTURE SCOPE

6.1 CONCLUSION

A Linear Variable Differential Capacitive Transducer (LVDCT) was successfully designed and implemented for the purpose of applying in automobile steering/braking system. The angle sensor realisation process was inexpensive as it required only ferrous steel plates, a glass mounting and a spindle. However the precision required in machining and alignment of glass and steel plates with respect to the spindle is very high. The hardware testing was carried out in which signal conditioning circuit based relaxation oscillator was built on NI ELVIS board. An appropriate task was created in LabVIEW so as to display the angle after mathematical calculations. The angle sensed by the transducer was displayed on the front panel of LabVIEW and it was found to be varying linearly with the change in capacitance of the sensor.

6.2 FUTURE SCOPE

The present system developed uses LabVIEW to display the readings. This restricts the portability of the system.in order to make the system independent/ stand-alone a LCD display can be integrated using a microcontroller.

APPENDIX

LF347 OPERATIONAL AMPLIFIER

GENERAL DESCRIPTION

The LF347 [10] is a low cost, high speed quad JFET input operational amplifier with an internally trimmed input offset voltage. The device requires a low supply current and yet maintains a large gain bandwidth product and a fast slew rate.

The LF347 may be used in applications such as high speed integrators, fast D/A converters, sample-and-hold circuits and many other circuits requiring low input offset voltage, low input bias current, high input impedance, high slew rate and wide bandwidth. The device has low noise and offset voltage drift.

FEATURES

The features of the Op Amp is as follows:

- Offset voltage: 5mV max
- Low Input bias current 50pA
- Wide gain bandwidth 4MHz
- High slew rate 13V/μs
- High input impedance $10^{12}\Omega$

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