ERROR ANALYSIS AND CHARACTERIZATION FOR OPTICAL ENCODERS

A PROJECT REPORT

submitted by

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to

the APJ Abdul Kalam Technological University
in partial fulfillment of the requirements for the award of the Degree

of

Master of Technology
in
Electrical and Electronics Engineering
with specialisation in
Industrial Instrumentation and Control

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JUNE 2023

DECLARATION

I undersigned hereby declare that the project report entitled "**Error Analysis and Characterization for Optical Encoders**", submitted for partial fulfillment of the requirements for the award of degree of Master of Technology in Electrical and Electronics Engineering with specialisation Industrial Instrumentation and Control, of the APJ Abdul Kalam Technological University, Kerala is a bonafide work done by me under supervision of *Ms. Ponmalar. M, Sci/Engr.'SF', SED/AIS, IISU*, *Assistant Prof. Dr. Resmi. R*, project Supervisor/ Internal Guide, Professor, Department of Electrical and Electronics Engineering, *Prof. Amal. A*, project Co-ordinator, Assistant Professor, Department of Electrical and Electronics Engineering, and *Prof. sumayya Jaleel*, Assistant Professor, Department of Electrical and Electronics Engineering. This submission represents my ideas in my own words and where ideas or words of others have been included. I have adequately and accurately cited and referenced the original sources. I also declare that I have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the institute and/or the University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been obtained. This report has not been previously formed the basis for the award of any degree, diploma or similar title of any other University.

Kollam
July 26, 2023

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CERTIFICATE

This is to certify that the Interim Report entitled " **Error Analysis and Characterization for Optical Encoders** " submitted by **Devika P** , **(Reg. No. TKM21EEII06)** of fourth semester to the APJ Abdul Kalam Technological University in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Electrical and Electronics Engineering with specialisation in Industrial Instrumentation and Control, is a bonafide record of the project work done by him under our guidance and supervision. This report in any form has not been submitted to any other University or Institute for any purpose.

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ACKNOWLEDGMENT

A lot of effort and hard work has been put into this project in course of its presentation. However, it would not have been possible without the kind support and help of many individuals and other sources. I would like to extend my sincere thanks to all of them. I take this opportunity to express my deep sense of gratitude and sincere thanks to all who helped me to complete this project report successfully.

I thank God Almighty for guiding me throughout the project. I express my sincere thanks to Dr.T A Shahul Hameed, Principal, TKM College of Engineering, for his encouragement in the completion of the project.

I thank *Dr. Sabeena Beevi K*, Head of the Department, Department of Electrical and Electronics Engineering and *Prof.Shanavas T N*, PG Co-ordinator, Department of Electrical and Electronics Engineering for their support and cooperation. I express my sincere gratitude to *Dr.Imthias Ahamed T P*, Head, centre for Artificial Intelligence, for his inspiring guidance and unstinted support.

I am greatly thankful to my internal guide, *Dr. Resmi. R*, Assistant Professor, Department of Electrical and Electronics Engineering, and my external guide Ms.Ponmalar.M, Sci/Engr.'SF', sensor electronics division /AIS, IISU for their supervision, assistance and helpful suggestions.

I am deeply indebted to *Prof.Amal. A*, Project Co-ordinator and Assistant Professor, Department of Electrical and Electronics Engineering, and *Prof.Sumayya Jaleel* , Assistant Professor, Department of Electrical and Electronics Engineering, for their excellent guidance, positive criticism and valuable comments.

Finally I thank my parents and friends near and dear ones who directly and indirectly contributed to the successful completion of my project presentation.

DEVIKA P

ABSTRACT

An optical encoder is a transducer that converts mechanical motion into electrical signals and is commonly used for precise position, velocity, and direction measurements. In space applications, optical encoders offer significant advantages, including high precision, non-contact sensing, compactness, reliability, low power consumption, and compatibility with digital systems. These benefits enable accurate and reliable position sensing and control of spacecraft components, contributing to mission success, resource optimisation, and improved spacecraft performance.

An absolute transmissive optical encoder with a resolution of approximately 19 bits is being sought for its high resolution and accuracy requirements. The output signal of this encoder exhibits various errors, including wide-angle and narrow-angle errors. Wide-angle errors are brought on by the eccentricity of the coded-disc axis of rotation, whereas narrow-angle errors are caused by spectral impurities and mismatches between sine and cosine signals. To identify and correct errors in both fine and coarse bits, fine rollover and coarse correction methods are employed. To minimize errors and enhance accuracy, several compensation techniques are utilized, such as normalization, linear interpolation, harmonic approximation, and the ratiometric technique. The effectiveness of these techniques is evaluated through phase difference analysis, amplitude mismatch analysis, and spectral analysis. This comprehensive approach aims to improve both accuracy and resolution.

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ABBREVIATIONS

AC	Alternating Current
AR	Anti Reflection
CMM	Coordinate Measuring Machines
CNT	Cos nonious track
C1MT	Cos master track 1
C2MT	Cos master track 2
DC	Direct Current
DOF	Degrees of Freedom
DSP	Digital Signal Processors
FE	Finite Element
GaAlAs	Gallium aluminum arsenide
GTE	Gear transmission error
IC	Integrated Circuit
IR LED	Infrared light-emitting diode
LED	Light emitting diode
LUT	Look up table
PD	Photo detector
STP	Sinusoidal transmissive pattern
SNT	Sin nonious track
S1MT	Sin master track 1
S2MT	Sin master track 2

NOTATIONS

a	Amplitude
θ	Absolute Angle
$C(\theta)$	Compensation signal
$E_O(\theta)$	Difference between output signal & triangular wave form
$V_C(\theta)$	Output cosine wave
V_{dc}	Volts direct current
V_{OL}	Piecewise linear output
$V_C(\theta)$	Cos output signal
$V_{CN}(\theta)$	Cos output signal of nonious track
$V_{CM}(\theta)$	Cos output signal of master track
V_{PK}	Peak Voltage
V_{PK-PK}	Peak to peak Voltage
$V_S(\theta)$	Sin output signal
$V_{SM}(\theta)$	Sin output signal of master track
$V_{SN}(\theta)$	Sin output signal of nonious track
p	Period
PT	Perfect triangular waveform

Chapter 1

INTRODUCTION

1.1 GENERAL BACKGROUND

Optical encoders are a typical form of transducer used to measure rotational motion. Commonly known as a "pulse generator," an optical encoder is a digital motion transducer. A light beam is deflected by a rotating disk with transparent slots. The amount of light transmitted and detected by a photo sensor determines the output of the transducer. It is composed of a shaft connected to a disk. The disk is round and has one or more alternately transparent and opaque tracks. On each side of each track, an optical sensor and a light source are placed. As the shaft rotates, the light sensor emits a sequence of pulses in response to the interruption of the light source by the pattern on the disk. This type of encoder uses an optical sensor to identify whether the light is on or off. This encoder is distinguished by two characteristics: high precision and powerful magnetic fields. Transmissive, reflecting, and diffraction-grating optical encoders are the three most common types. As spinning disks, glass or very thin stainless steel plates are used.

1.2 TYPES OF OPTICAL ENCODERS

Optical encoders are classified by, the direction of motion to be measured, the signal output method, and the optical path.

1.2.1 Direction of motion to be measured

1. **Optical linear encoder:** This type of encoder emits light onto a pattern of slits that moves along a linear axis. A sensor detects the light that passes through the pattern (or is reflected by it) and utilises that information to determine its position.

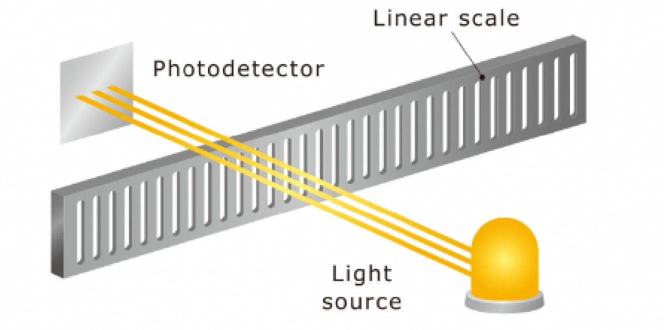


Figure 1.1: Optical Linear encoder

2. **Optical rotary encoder:** This type of encoder emits a light beam onto a pattern of rotating slits. A sensor detects the light that passes through (or is reflected by) a sensor and transmits it as position data.

   Optical rotary encoder is used as a sensors in robotics. It is capable of reading a disk with properly spaced graduations. It uses a code wheel with a rounded linear scale, which is a component of a linear encoder; both are manufactured using similar processes. They are employed in a vast array of applications, ranging from affordable printer applications to high-precision control and measurement applications.

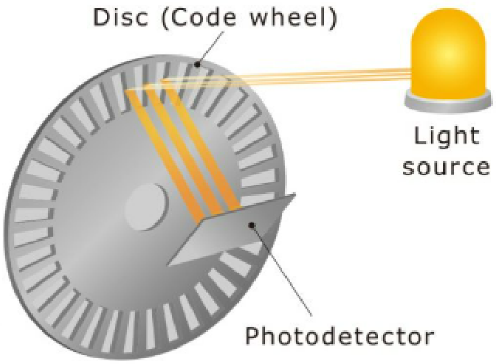


Figure 1.2: Optical Rotary encoder

1.2.2 Signal output method

1. **Incremental type:** To determine the rotation angle, the total number of detected pulses is rounded to the nearest decimal. The interval between pulses or the number of pulses per unit of time can be used to calculate the rotation speed. In the incremental type, only the change in disk rotation is known, and the number of degrees the sensor output has varied from its reference position is recorded and stored in a counter or memory.

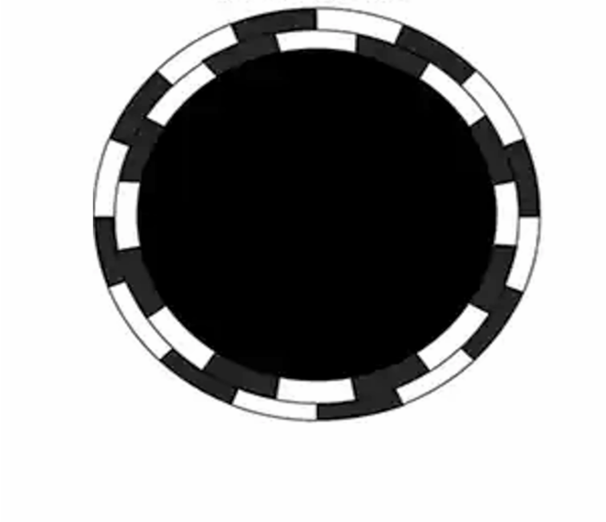


Figure 1.3: Optical Incremental type encoder

2. **Absolute type:** This particular type of encoder outputs the absolute value of the rotation angle and the mechanical position it has obtained as quickly as it is switched on.

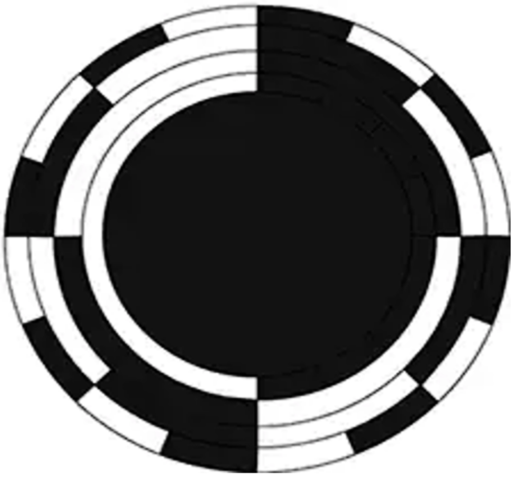


Figure 1.4: Optical Absolute type encoder

The absolute type produces a one-to-one correspondence between the disk angle of the scale pattern and the output code, whereas the incremental type produces only incremental values and requires origin alignment. Therefore, regardless of the power state of the absolute type, the absolute angle is always known. Consequently, the absolute type has the advantage of not requiring origin alignment, but the scale pattern is typically more complex and the resolution is typically lower than with the incremental type.

1.2.3 Optical path

According to the optical path the light-detecting element within an optical encoder takes to detect light, different types of optical encoders can be classified as transmission or reflection types.

1. **Transmissive type:** When a light source and a light-receiving equipment are placed across a distance from one another, light is either intercepted or transmitted. This technique is known as a transmission type.

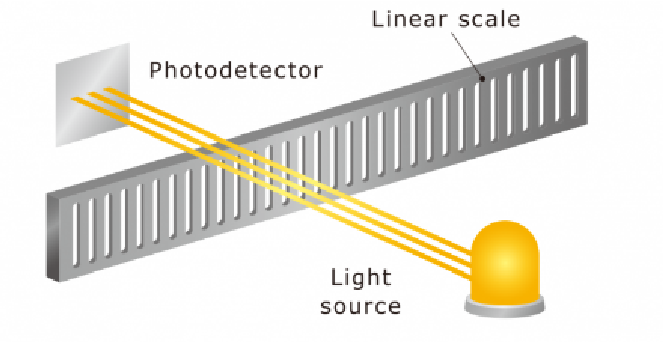


Figure 1.5: Optical Transmissive type encoder

2. **Reflective type:** The term "reflective type" refers to the technique in which the light source and light-receiving element are positioned on the same plane, and a component that switches between reflection and non-reflection of light is positioned above the light source and light-receiving element.

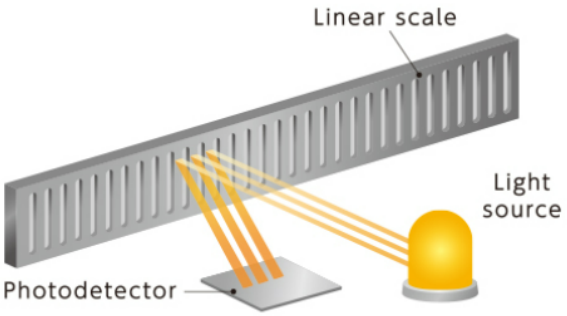


Figure 1.6: Optical Reflective type encoder

1.3 OPTICAL ENCODER STRUCTURE

1. **Light source:** Infrared light-emitting diodes are the most common light source for optical encoders. The product with high resolution may alternatively be laser diodes.

2. **Photo detector:** The typical light-receiving component is a photo detector or other similar device. A diode serves as the light-receiving component, and it uses light to convey the input signal and current to the output side.

3. **Encoder scale:** Encoder scales are parts incorporated into encoders that change whether light is transmitted, stopped, or reflected or not reflected (e.g.Light emitting diodes). The scale is engraved with scales at regular intervals, and the kind of light that passes through or is blocked by the scales is referred to as the transmission type, while the type of light that reflects or does not reflect is referred to as the reflection type.

   Encoder scales are indispensable components for motion control technology and are used in many fields, including industrial robots, positioning servos, production plant automation, and the automotive industry.

1.4 OPTICAL ENCODER WORKING PRINCIPLE

An optical transmissive rotary encoder is used as an example to demonstrate the basic workings of optical encoders. The principal components of this kind of encoder are,

1. Light source (on the Infrared LED side)

2. Photo detector (on the Photo IC side)

3. Encoder disk engraved with bars that serve as scales

The optical encoder disk, which is used to measure the number of rotations of the motor, is mounted between the U-shaped parts shown in the illustration. This U-shaped part is called a "photo interrupter". The photo interrupter contains an infrared LED and a photo IC placed between the disks. When infrared light is irradiated, this mechanical part measures the number of times the LED light passes through the bar hole of the disk. The number is converted into an angle to detect the rotation angle and speed of the disk.

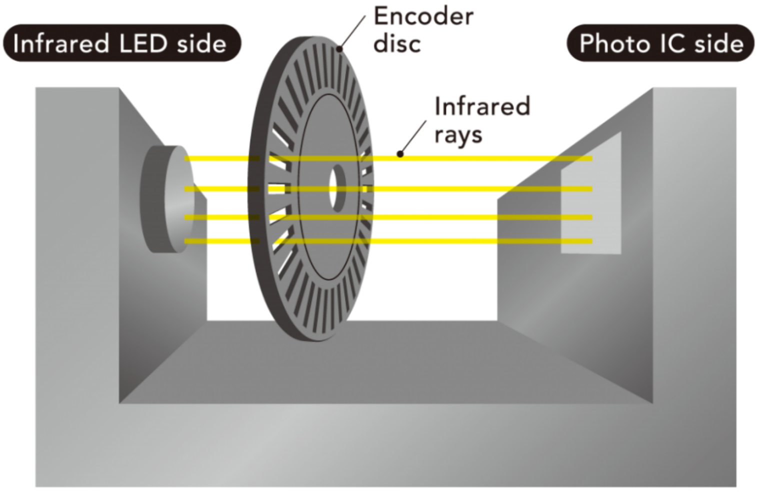


Figure 1.7: Transparent type optical encoder

1.5 OPTICAL ENCODER SELECTION

1. **Model** (Linear or Rotary)
   - Determine whether to use a rotary or linear encoder as the first stage in the encoder selection process.
   - Depending on whether the drive system will ultimately move in a linear or rotational direction, one can choose an encoder.
2. **Output method** (Incremental or Absolute)
   - In contrast to incremental types, which need focusing and may need for several expensive sensors, absolute types may provide absolute location information even when the power is off. This means that absolute types do not need training.

- The incremental type encoder is simple in construction and cost effective. In addition to monitoring absolute values, the incremental type is used to measure velocity and direction of motion.

3. **Resolution and Specifications**

   - It is typical to choose a resolution that offers 1/2 to 1/4 of the overall precision of the mechanical system.
   - According to the system in which the encoder will be used, dimensions should be chosen. In other words, the output shaft diameter (solid shaft or hollow shaft), length, and other dimensions must be chosen.
   - Consider a custom-made encoder if you are unable to obtain an encoder with the required resolution and size off the shelf.

1.6 USES OF OPTICAL ENCODERS

1. **Joints of Robot Arm**: There are many different mechanical position/posture sensor types, however producers in the robotics sector often utilise articulated arms with rotary encoders located at the joints. Depending on the number of joints to be measured, one of two types of 3-DOF (Degrees of Freedom) or 6-DOF sensors must be used: one that measures simply position, and the other that measures position plus posture. In some unique circumstances, it is also possible to quantify human movement using a motion capture equipment that has encoders positioned at the joints of the body.

2. **Doors of Elevator**: Due to the near closeness of the passengers, a motor that controls the elevator door's opening and closing needs to be silent. The speed at which the door moves is managed by an encoder in the motor. The location of the doors is also made easier to predict.

3. **Printers**: The functioning of the ink heads in inkjet printers is managed by encoders. In response to the associated pulley rotating, the encoder pulse signals to the industrial inkjet printer. In order to determine an object's speed, the inkjet printer measures the time between pulse signals. Printing may be done neatly and precisely thanks to the encoder in

the printer. Additionally, encoders are employed to regulate the paper-moving spinning drum.

4. **Machine tools**: Encoders are used to regulate the table's horizontal movement, which is where the workpiece is set up. For instance, finishing precision on NC milling and electrical discharge machines must be in the range of a few microns to a few tens of microns. They need encoders that have a resolution that is around ten times greater than the needed finishing precision to do this.

1.7 OBJECTIVES

Optical encoders are a common type of transducer used to measure rotational motion. It consists of a shaft attached to a circular disk with one or more tracks that have regularly transparent and opaque areas. On opposing sides of each track is a light source and an optical sensor. As the shaft rotates, the light sensor emits a sequence of pulses in response to the interruption of the light source by the pattern on the disk. This signal's compatibility with digital circuitry may be complete. Since the number of output pulses per rotation of the disk is known,the number of output pulses per second may be used to directly convert the number of output pulses per second to the rotational speed of the shaft (or rotations per second). The photodetector is responsible for generating the output. The output is a waveform, such as the sine and cosine wave patterns. This waveform has a number of errors, including wide angle errors, peak errors, peak-to-peak errors, and narrow angle errors. This project's primary objective is to eliminate these optical encoder-related errors. Other important aims include;

- Identifying and classifying errors in existing encoders.
- Characterization of error with respect to environment.
- Control loop design to reduce the error.

1.8 SCOPE

The scope of this project encompasses the analysis and compensation techniques for reducing errors in optical encoders. The project aims to explore various error sources, classification of errors based on wide angle and narrow angle errors, and the impact of these errors on the accuracy and performance of optical encoders. Additionally, the project focuses on the development and application of compensation techniques to mitigate these errors and improve overall system performance.

The project includes studying different types of optical encoders, such as 19-bit encoders and Nonious encoders, and understanding their design configurations and principles. The analysis methods employed to identify specific error sources, including phase difference analysis, amplitude mismatch analysis, and spectral analysis, will be investigated. The project also involves examining the effectiveness of compensation techniques such as normalization, linear interpolation, harmonic approximation, and the ratiometric technique in reducing errors and improving accuracy.

The scope further encompasses the experimental validation of these techniques and their application in real-world scenarios. The project will explore the impact of factors such as reference values and bit configurations on error correction.

It is important to note that the project focuses on the analysis and compensation of errors in optical encoders and does not cover the design or manufacturing aspects of the encoders themselves. The scope is limited to error analysis, compensation techniques, and their application in improving accuracy and performance.

Future research and development in the field of optical encoders are highlighted, such as exploring additional error sources, advanced compensation algorithms, standardization efforts, and continuous monitoring and maintenance practices.

1.9 SCHEME OF WORK

This project consists of several chapters addressing various aspects of optical encoder analysis and compensation. Chapter 1 introduces the topic and sets the context for the research. Chapter 2 reviews existing literature and studies related to optical encoders, including error sources and compensation techniques. Chapter 3 discusses the design of a 19-bit optical encoder and its configuration, including components and encoding schemes. Chapter 4 analyzes errors in optical encoders, including wide angle and narrow angle errors, and their impact on performance and accuracy. Chapter 5 explores techniques for improving accuracy, such as normalization, linear interpolation, and harmonic approximation, and their implementation and effectiveness.

Chapter 6 focuses on Nonious encoder design and configuration, including master and Nonious track arrangement and resolution calculations. Chapter 7 explores compensation techniques for reducing errors in optical encoders, such as ratio metric compensation and harmonic cancellation. Chapter 8 summarizes key findings and insights from the research and discusses the future scope of the project, suggesting potential areas for further exploration and improvement in the field. The logical sequence of the scheme of work ensures a comprehensive exploration of the topic while ensuring a logical flow of information.

Chapter 2

LITERATURE REVIEW

2.1 GENERAL BACKGROUND

In 1951, optical encoders [1] were developed in response to the need for more resolution than was achievable with other sensor types, as well as longer life than was possible with brush encoders at the time. In the years that followed, optical encoders built out a solid position in precise pointing and tracking applications, and by the time the first satellites were launched, they were well-established. The increase in use of optical encoders in space has been directly attributable to the development of light sources with extended lifetimes. Initially, several light sources were used, but they were gradually phased out as better alternatives became available. There were neon lamps, xenon flash tubes, and incandescent bulbs, among others. All of these light sources have been used to construct optical encoders that have operated magnificently in space throughout the duration of the light source's lifetime. All of these light sources have been used to construct optical encoders that have operated excellently in space for the duration of their lifespans. For example, Fig 2.1 shows the first high-resolution optical encoder used in space.The light-emitting diode (LED) is the most popular light source used today for both ground and space applications. This solid-state semiconductor emits light for extremely long lives with no degradation. First optical encoder used in space that was illuminated by gallium arsenide LEDs.

The simplest optical encoder consists of a collimated light source. a lamp or LED, a rotating code disc with a specified pattern, a slit plate, grating, or optic to define the optical beam, and a detector or detector assembly that receives the encoded light beams and converts them to electrical current. The detectors' encoded outputs are amplified to digital levels, formatted,

Figure 2.1: First Optical encoder used in space craft applications

and output in digital format. In the majority of cases, the optical encoder requires no further excitation beyond the mechanical shaft movement and appropriate DC power for the LEDs and electronics. The purpose of the slit plate, grating, or optic is to limit the light beam's angular dispersion to slightly less than one-half cycle of the pattern on the code disc. If this is not done, the output count will not be determined by the pattern on the code disk.

The most of encoders used in space today are defined by two fundamental code disc data concepts. The incremental encoder and the absolute encoder. The disc code patterns of incremental and absolute encoders, as well as their solutions, are detailed in [2]. The input and output formats of an optical encoder, as well as their characterisation, are also discussed in detail, as are the numerous encoder errors.

Optical encoders can be designed to operate in virtually any environment, including space. The problems associated with employing encoders in space are well known. By focusing on design details, it is possible to overcome the challenge of creating an encoder with optimal performance in harsh shock, vibration, temperature, vacuum, and radiation conditions. For every instance of an optical encoder failure, there are many instances in which both applications and customers are entirely satisfied. Based on expertise with the space environment, the distinction lies in the attention to design details.

Dr. Harold S. Johnson, an electrical engineer at the Massachusetts Institute of Technology (MIT), created the first optical encoder in the early 1960s. Dr. Johnson's invention revolutionised position sensing technology by introducing the concept of using light and photodetectors to detect position changes. In recent years, there have been significant developments in the field of optical encoders. These advancements have led to the creation of numerous encoder designs with enhanced features and capabilities. Optical encoders have seen improvements in terms of resolution, accuracy, speed, compactness, and reliability. Recent developments in optical encoders have allowed for the creation of cost-effective and reliable solutions that address the need for rotor position and speed information in motor control [3], particularly in automation applications.

2.2 PREVIOUS WORK RELATED TO DESIGN OF OPTICAL ENCODER

Magnetic rotary encoders are simple structures with quick response, resistance to humid environments, multi-function capabilities, and small power dissipation [4]. They are expected to be widely used in office automation, factory automation, automotive engine control, and home automation applications.

In addition to magnetic rotary encoders, advancements in integrated optical encoder designs have been made. One design uses a laser diode, monolithic photodiodes, and a fluorinated polyimide waveguide to measure grating scale movement and relative displacement. This compact encoder design integrates bulky components and uses two beams emitted from laser diode mirrors.

For precise linear position measurement in computer-controlled manufacturing machinery, a glass scale with a light-emitting diode and two code tracks is used in an optical linear position encoder. This encoder [5] achieves a resolution of 10 nm and an accuracy of better than 100 nm over short distances.

Compact optical encoders [6] for measuring linear displacement use micromachining techniques, enabling second-order grating imaging under incoherent illumination, resulting in high-contrast encoder signals. A novel interpolation method generates high-order sinusoids and uses an offline look-up table [7] for inferencing, compensating for encoder imperfections and showcasing improved resolution.

A high-accuracy optical encoder developed using advanced disc technology achieves a 30-bit resolution [8], surpassing the accuracy of traditional drawing machines. Future research focuses on high-precision angle sensor measurement machines, encoders exceeding 30 bits, and absolute encoders with self-calibration systems.In magnetic encoders [9], the importance of understanding their design principles for optimal application selection is emphasised.

Understanding design principles for optimal application selection is crucial in optical encoders. An optical high-resolution readhead chip [10] has been developed for Renishaw high-precision meteorology systems, enabling simultaneous device alignment through wafer-level photolithography and improving alignment tolerances. These advancements in optical encoders have led to various applications in space-based systems [11], laser communication systems[12], high-precision pointing [13],[14], and more. Techniques such as signal conditioning, interpolation, and real-time processing are crucial for interfacing and achieving high-resolution position interpolation. An incremental encoder is designed to convert angular motion into electrical signals. It provides information about the relative position changes and direction of rotation. On the other hand, an optical rotary encoder utilizes precise sinusoidal transmissive patterns [15] to detect shaft rotation. This type of encoder offers high accuracy and resolution in measuring angular displacement.

In, recent developments in optical encoders have expanded their capabilities and applications, enabling precise position measurement[16], compact designs [17], improved resolution [18], and enhanced performance in various industries and systems.

2.3 PREVIOUS WORK RELATED TO IDENTIFY THE ERRORS IN OPTICAL ENCODER

A low-pulse-per-revolution optical encoder technique for measuring gear transmission error (GTE) [19] at high speed, utilizing low-priced components and a high-frequency timer to estimate encoder pulse lengths. The precision of the measurement is dependent on the shaft's angular speed, with a coherence of less than 0.03 seconds per arc for each frequency of power spectral density. Calibration using a specific test rig results in insignificant improvements in precision measurement, with a coherence of less than 0.03 seconds per arc for each frequency

Table 2.1: Comparison of proposed and existing encoders

Comparison of proposed and existing encoders			
Sl. No	Encoder type	Features	Outcome
1	Diffractive type	An imaging sensor has sensed an angle of acceleration sensed from a diffractive solid measure on a microstructured plastic disk by an imaging sensor.	Available resolution: 15 bits
2	Polarization type	Angular acceleration has been achieved from the differential light intensity of the orthogonal polarisation components.	Stable, differential signal matching the theoretical Malus law was obtained
3	Ratiometric type	Angular information is determined by the ratio of the transmitted and reflected light power	The accuracy is 0.53% over the full range of 0° to 180°
4	Binary type	Angular information is determined from lines and windows printed on a transparent disk	Maximal available resolution via interpolation:22bits
5	Magnetic type	Angular information is calculated from AC signals provided by Hall effect devices	Available resolution with accuracy to 0.3° :13 bits
6	STP type	Angular acceleration has been sensed from a bell-shaped sinusoidal transmissive pattern by an imaging sensor.	Available resolution: 15 bits,high accuracy

of power spectral density. This cost-effective and straightforward encoder technique enables transmission error measurement with high precision and reliability in mechanical systems.

A method is presented to suppress systematic errors [20] in resolvers and optical encoders with sinusoidal line signals, improving drive system dynamics and smooth-running characteristics without requiring additional hardware or computational effort. A metrology approach [21] is discussed for below 100 nm range measurements using large fiducial grid optical encoders and nanometer-accuracy encoder plates.

To overcome resolution and accuracy limitations of optical incremental encoders, a method based on time stamping [22] is proposed, utilizing stored events captured at a high-resolution clock. Real-time experiments show significant improvements in position accuracy (up to 87%)

and more accurate estimated velocity compared to differentiated quantized encoder output signals.

Error analysis of optical encoders is explored, focusing on optical, mechanical, and electronic factors that can affect measurement accuracy. A linear expansion method [23] is presented to estimate and analyze errors produced in optical encoders, which is experimentally verified to improve encoder design and accuracy.

Recent studies have investigated the encoder itself as a source of error in positioning machine tools' movable parts, focusing on sensor loss due to vibration under different mounting conditions [24]. Thermal error analysis for absolute angular encoders [25] is also discussed, employing finite element analysis and experimental investigations to enhance optical performance.

A novel rotary optical encoder for eccentricity self-detection [26] is presented, utilizing a spider-web-patterned scale grating and a dual-head scanning unit for synchronous measurements of angular and radial displacements. The feasibility and effectiveness of the proposed encoder are demonstrated through experimental results aligning with optical microscope measurements.

2.4 COMPENSATION TECHNIQUES FOR ERROR ELIMINATION

A low-pulse-per-revolution optical encoder technique for measuring gear transmission error (GTE) at high speed, utilizing low-priced components and a high-frequency timer to estimate encoder pulse lengths. The precision of the measurement depends on the shaft's angular speed, with a coherence of less than 0.03 seconds per arc for each frequency of power spectral density. Calibration using a specific test [27] rig results in insignificant improvements in precision measurement.

A metrology approachis discussed for below 100 nm range measurements using large fiducial grid optical encoders and nanometer-accuracy encoder plates. A method based on time stamping is proposed to overcome resolution and accuracy limitations of optical incremental encoders. A new design eliminates interpolation errors in optical encoders by using [28] sine-function transmissivity gratings as index gratings, reducing harmonic errors and producing various types of sine-index gratings. An error compensator fixes errors in real-time, reducing non-orthogonal error, amplitude inequality, and residual dc voltages.

A Simulink-based method [29] is proposed for estimating angular velocity using incremental optical encoders, minimizing quantization error in conventional period counting techniques. The proposed scheme converts sinusoidal signals into linear output signals [30], allowing precise displacement determination using a linear equation. The converter achieves a non-linearity error below 0.0029 m for a linear optical encoder with a 20 m period and demonstrates robustness against signal amplitude imbalance.

An experimental-theoretical method [31]is presented for identifying and compensating static errors in optical encoder phase coordinates, specifically for angle measurements. A method is introduced for collecting data from an optical position-or-angle encoder to determine short-range errors and generate a compensation function [32].

A proposed optical, analogue, self-referencing, ratio-metric [33] smart displacement sensor offers reliable measurement of rotational position independent of power fluctuations, making it suitable for avionic applications. Electronic interpolation is crucial for improving optical encoder measurement resolution. The impact of temperature on optical linear encoder error is investigated, and an incremental error model is built using various methods [34]. Accurate and reliable calibration is achieved by following manufacturer's tolerances and comparing measured errors with reconstructed errors.

The paper presents an experimental [35] real-time compensation model [36] for geometric and thermal errors in optical linear encoders, utilizing a parametric function and a linear nature error [37] component based on ambient temperature variation [38], resulting in a significant reduction in final positioning error.

2.5 SUMMARY

This chapter gives an overview of optical encoders. It first discusses the fundamental ideas and principles at play. The chapter also examines the development of the first optical encoder as well as earlier studies that were done in the area. To obtain the necessary information and insights, review papers that are pertinent to the subject of this study are analysed. The diverse types of faults that can happen as well as the analysis techniques required to measure and comprehend these flaws are all topics covered in these articles on various facets of optical encoder design.

The calibration procedures used for optical encoders are also covered in detail in this chapter because good calibration is essential for obtaining accurate results. The accuracy and performance of optical encoders can be improved by exploring a variety of compensation approaches to remove the faults that are built into them.

Overall, this chapter offers a thorough foundation for comprehending optical encoder design, faults, analysis, calibration, and compensation methods.

Chapter 3

DESIGN OF THE ENCODER

3.1 OVERVIEW

An optical encoder serves as a crucial angular sensor within position and speed control systems. Its primary purpose lies in governing the motors of machines, robots, and satellites. It would not be an exaggeration to assert that optical encoders are essential for enabling angle detection in a wide range of movable components, driven by an inherent necessity. The standout characteristic of encoders is their ability to directly detect digital signals, making them highly accurate sensors. Notably, within office equipment, machine tools, and industrial robots, optical encoders find widespread utilisation as high-precision position control sensors.

The central focus of this project revolves around the integration of optical encoders into satellites, with the aim of enhancing angular resolution. To achieve this objective, our design entails the creation of a 19-bit optical encoder, a crucial step towards advancing accuracy and resolution. In the realm of space mechanisms, there is a strong demand for position measuring equipment that possesses both high resolution and accuracy. Optical encoders emerge as a recommended solution due to their precise measurement of rotary angular positions, making them ideal for applications requiring meticulous motion or velocity control in space.

Among the various angular position measuring devices available, optical encoders reign supreme in terms of accuracy. Thus, our endeavour involves the development of a 19-bit optical encoder that will provide an absolute angular position with exceptional resolution and accuracy, catering specifically to the requirements of space mechanisms such as spacecraft actuators and velocity controllers. To optimise performance, the optical disk design will incorporate grey coding for 13 bits, ensuring efficient encoding and decoding. Additionally, through the processing of sinusoidal quadrature signals, an additional 6 bits, referred to as fine bits," will be obtained, further refining the encoder's precision capabilities.

3.2 DESIGN CONFIGURATION

To design an optical encoder with high resolution and accuracy for measuring absolute angular position information of rotating space mechanisms, several fundamental components are essential. These components form the foundation of the encoder's functionality and precision. The following are the key components required:

1. A coded disk mounted on the rotor.
2. A reticule disk mounted on the stator.
3. Electronics with light source and detector mounted to the stator.

In the assembly of the optical encoder, the primary component mounted to the rotating mechanism, known as the rotor, is the coded disk. The coded disk features specific patterns or tracks that interact with the light source and detector to determine the angular position. Contrastingly, the remaining parts of the optical encoder, namely the reticule disk, light source, and detector, are mounted to the stationary component known as the stator. The reticule disk assists in aligning the light beam and patterns on the coded disk, while the light source emits the light used for position detection, and the detector captures the light after it interacts with the patterns on the coded disk.

The objective of our design is to create a 19-bit optical encoder that provides angular position data of the absolute type. This encoder is specifically tailored to meet the high resolution and accuracy requirements for space mechanisms, such as spacecraft actuators and velocity controllers. By accurately measuring the angular position, the encoder aids in precise control and operation of these mechanisms, ensuring optimal performance in space applications.

3.2.1 Coded-disk design

For the patterning of the coded disk, we have selected glass as the base material, which is coated with chromium in regions where a dark condition is required at the detector side. The remaining portion of the disk is transparent. This selective coating allows for specific areas to block or transmit light, enabling the detection of position information.

In our design, we have chosen to use gray code for the patterns written on the disk. Gray code is preferred because it ensures that the difference between successive bit counts is only a single bit. This characteristic enables achieving a single bit resolution at every instant of measurement.

The chromium coating used on the glass disk has a transmissivity of only 0.2%, meaning that it blocks the majority of light. This property is essential for creating the dark regions on the coded disk, which are crucial for accurate position detection. Glass has been selected as the material for the disk due to its unique properties, including mechanical stability, dimensional stability over a wide temperature range, and its ability to withstand shock and vibration. These properties are crucial for maintaining the integrity and accuracy of the optical encoder in various environmental conditions and operational scenarios.

The implementation of the 13-bit encoder requires a disk radius that is suitable for accommodating the patterns and providing sufficient resolution for the desired measurements. The specific size or radius of the disk would depend on the design specifications and requirements of the encoder.To create the geometric patterns on the optical disk, state-of-the-art maskless laser lithography techniques are utilized. This advanced method allows for precise engraving of the patterns onto the glass surface, ensuring accurate and reliable position detection.

Figure 3.1: Gray coded Disk

Overall, our current design incorporates a 13-bit gray code (fig 3.1), engraved onto a glass disk, which provides the necessary resolution and accuracy for the intended application of the optical encoder.

3.2.2 Reticule disk design

The reticule disk plays a crucial role in controlling the amount of light that passes from the source to the detector through the patterned glass disk. Its purpose is to limit the angular dispersion of the light beam onto the coded pattern, ensuring precise regeneration of the patterns on the photodetector side.

Several factors come into play in determining the accuracy of the coded patterns, including the dimensions of the reticule, its orientation with respect to other optical elements, and the distances between the source, reticule, coded disk, and the detector. The reticule design and implementation are essential to restricting the dispersion of light at the edges of the coded disk apertures. Excessive dispersion can cause distortions in the detected signals due to higher-order diffraction patterns. By carefully designing the reticule, these distortions can be minimised, leading to a cleaner and more accurate output from the detector.

The dimension of the reticule is critical in achieving the desired balance. It should be chosen to minimize light spread and diffraction effects, thereby reducing distortions in the detected signals. However, it is also important to ensure that sufficient light reaches the detector plane to maintain an adequate signal level. By optimizing the reticule design, taking into account the aforementioned factors, it is possible to control the amount of light spread over the photodetector plane and minimize diffraction-related distortions. This ensures accurate and reliable detection of the coded patterns and improves the overall performance of the optical encoder system.

3.2.3 Encoder Source and Detectors

In our design of the 19-bit optical encoder, we have chosen to utilize silicon-based phototransistors as the photodetectors. The selection of silicon phototransistors offers advantages in terms of mechanical alignment accuracy, allowing for improved precision in detecting the light patterns.

To ensure optimal performance and compatibility with the phototransistors, we have selected GaAlAs (Gallium Aluminum Arsenide) infrared LEDs as the optical source. The choice of GaAlAs infrared LEDs is based on their peak sensitivity wavelength, which matches the range of sensitivity of the silicon phototransistors. This wavelength alignment helps to maximize the efficiency of light detection and enhance the overall accuracy of the optical encoder system.

By utilizing array-based silicon phototransistors and GaAlAs infrared LEDs, our design aims to achieve high sensitivity and accuracy in capturing the encoded light patterns, thereby improving the reliability and performance of the optical encoder for precise angular position measurements.

3.3 OPERATING PRINCIPLE

The operating principle of the designed optical encoder is based on the transmission type configuration is shown in Fig 3.2. In this setup, an array of photo sources, consisting of infrared LEDs, is positioned on one side of the coded disk. On the opposite side, a corresponding array of phototransistors is placed to act as the photo detectors. The coded disk, which contains the encoded patterns, is located between the photo source array and the photo detector array.

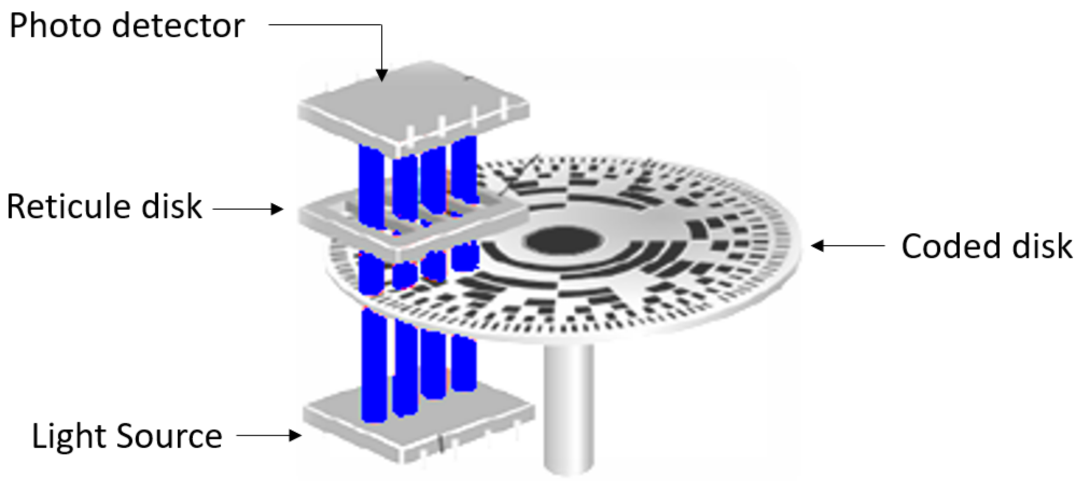


Figure 3.2: Schematic of transmissive type absolute rotary optical encoder

When the infrared LEDs emit light, the optical signals pass through the coded disk, which acts as a medium for the transmission of these signals. The patterns on the coded disk modulate the light, creating variations in intensity or blocking certain portions of the light. These patterns represent the angular position information being measured.

The transmitted light signals are then received directly by series of phototransistors array. The phototransistors, which are sensitive to infrared light, convert the received optical signals into corresponding electrical signals. The variations in the detected light intensity due to the coded patterns on the disk result in electrical signals that carry information about the angular position.

To ensure precise detection and improve the quality of the electrical output, a reticule disk is employed in the design. The reticule disk helps limit the amount of light reaching the photodetectors, thereby enhancing the detection of a clean sinusoidal waveform. By controlling the dispersion and minimizing diffraction effects, the reticule disk contributes to obtaining an accurate and well-defined output from the photo detector array.

Overall, the transmission type optical encoder design utilizes infrared LEDs as photo sources, matching phototransistors as photo detectors, and a reticule disk to optimize the transmission of optical signals and ensure accurate measurement of the angular position.

3.4 OPTICAL LAYOUT

- The light beam passes through the reticule and the rotor disk and falls on the photo detector.
- The rotor contains opaque and transparent apertures on a glass disk, and the widths of the apertures on the reticule and the rotor disc are different for different tracks.
- Based on the sizes of the apertures and the distance between the optical elements, the intensity pattern of light reaching the detector is analysed.

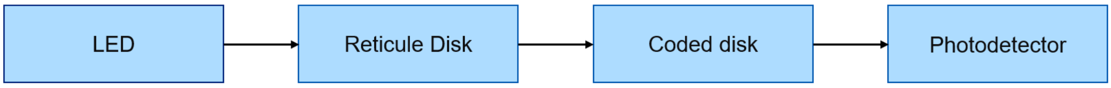


Figure 3.3: Optical layout of Optical encoder

Following Fig 3.3 and Fig 3.4 gives the optical lay out of an optical encoder and diverging LED source

The Fig 3.4 illustrates the issue of LED divergence in an optical encoder system. LED divergence refers to the spreading out or dispersion of light emitted from the LED source. This

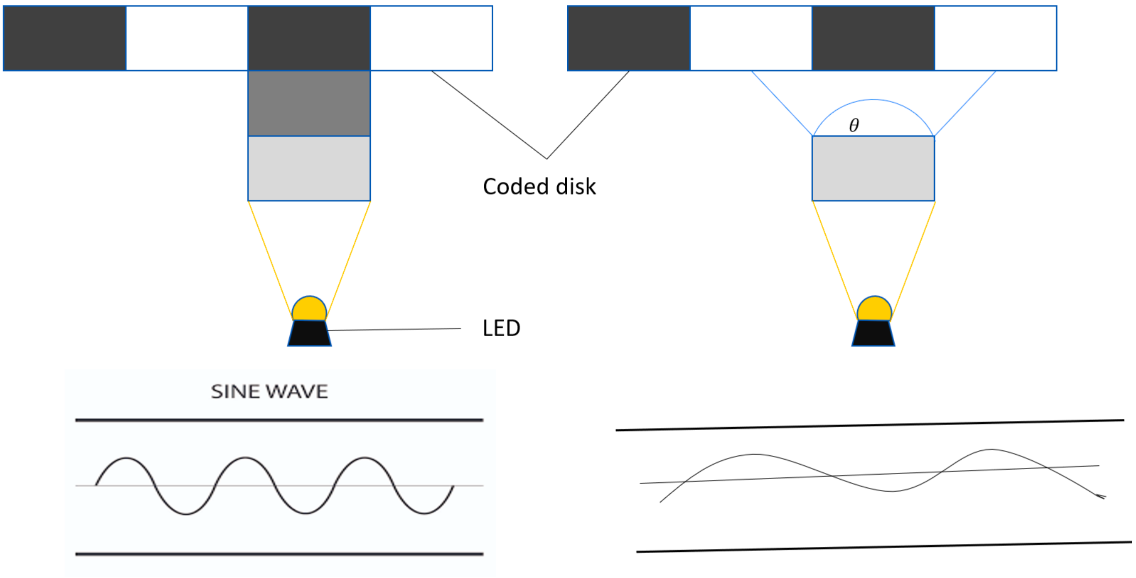


Figure 3.4: Divergence of LED

divergence causes multiple apertures on the rotor disk to be exposed to the scattered light, resulting in inaccurate or non-optimal signals.

Ideally, when the LED light passes through the coded disk in the encoder, the desired output should be a clean and pure sine wave signal. However, in reality, the LED light source emits light that diverges and spreads out beyond the intended area. As a result, more LEDs are placed in the light-emitting section to compensate for the divergence, but this causes the light to scatter and interact with adjacent patterns on the disk, leading to unclear and distorted output signals.

To mitigate this issue, a reticule disk is used in the encoder system. The reticule disk serves as a means to limit the light emitted by the LEDs, helping to reduce the effects of LED divergence and improve the clarity and accuracy of the output signals. By utilizing the reticule disk, the unwanted scattering and interference caused by the diverging LED light can be minimized, ensuring better performance and reliable signal generation in the optical encoder system.

3.5 PARAMETERS IN OPTICAL ENCODER

3.5.1 Coarse Bits

The optical encoder generates absolute gray coded track bits based on the excitation of the infrared (IR) LED at the phototransistor output. These track bits represent the angular position information obtained from the rotation of the coded disk.

The track bits, also referred to as coarse bits or low-resolution bits, transition between high and low levels at the output of the photodetector. This transition occurs as the coded disk rotates and different apertures align with the light beam, modulating the photocurrent generated by the IR LED excitation. The photocurrent is then converted into voltage. The coarse bit outputs exhibit a trapezoidal waveform due to the nature of the track pattern on the coded disk. These analog coarse outputs are fed into analog comparators, which compare the voltage levels to a reference threshold. The analog comparators generate digital bit output pulses based on the comparison results.

The generated digital bit outputs represent the high-resolution position information and are used for further digital signal processing (DSP) or data interpretation. These digital outputs provide a more precise representation of the absolute angular position of the encoder disk compared to the coarse analog outputs.

3.5.2 Fine Bits

Fine bits are high-resolution bits that are derived from the sine-cosine quadrature signal outputs from the encoder. These bits are produced by a high-resolution DSP interpolation method called interpolation. Quadrature signals are processed to minimise offset errors and amplitude imbalances. These errors are filtered before deriving the high-resolution bits.

3.6 SUMMARY

This chapter discusses the design and working principles of optical encoders, focusing on transmissive-reflective types. The encoder consists of a reticule disk, LED source, rotor disk, and photo detector. The reticule disk limits light from the LED source to the detector, while the rotor disk contains apertures of different widths. The alignment of these apertures changes as the rotor disk rotates, modulating the intensity pattern of light reaching the detector. The optical layout of the encoder includes the placement of the reticule, rotor disk, and detector in the optical path.

The LED source emits light, while a photo detector detects the modulated light. The reticule and rotor disks are typically glass and contain apertures for controlling light transmission. The design of optical encoders considers various parameters, such as aperture size, distance between optical elements, and modulation of intensity pattern, to achieve high-resolution and accurate position measurements.

Chapter 4

ERROR IN OPTICAL ENCODER

4.1 OVERVIEW

This chapter discusses encoder types and their impact on wide-angle error and narrow-angle error. Wide-angle error occurs when the encoder experiences large angular displacement, and addressing it is crucial for accurate and reliable measurements. Narrow-angle error, on the other hand, occurs when the encoder experiences small displacements and is influenced by factors like sensor resolution, quantization noise, and signal processing techniques. Minimizing narrow angle error is essential for precise measurements in applications with fine angular resolutions.

4.2 ERROR CLASSIFICATION

The Fig 4.1 represents a typical error plot of an optical encoder. It is used to visualize and analyze various types of errors encountered in the operation of the encoder. The plot includes different error measurements such as wide angle error, narrow angle error, peak error, peak-to-peak error etc.

4.2.1 Wide Angle Error

Wide-angle errors in encoders are caused by the eccentricity of the coded disk axis of rotation relative to the rotating mechanical component. Measurement of eccentricity and eccentric phase angle can change mechanical periodicity and compensate for these flaws. Fig 4.2 is the Wide-angle error in encoders is uncertainty in alignment between the spindle axis of rotation and

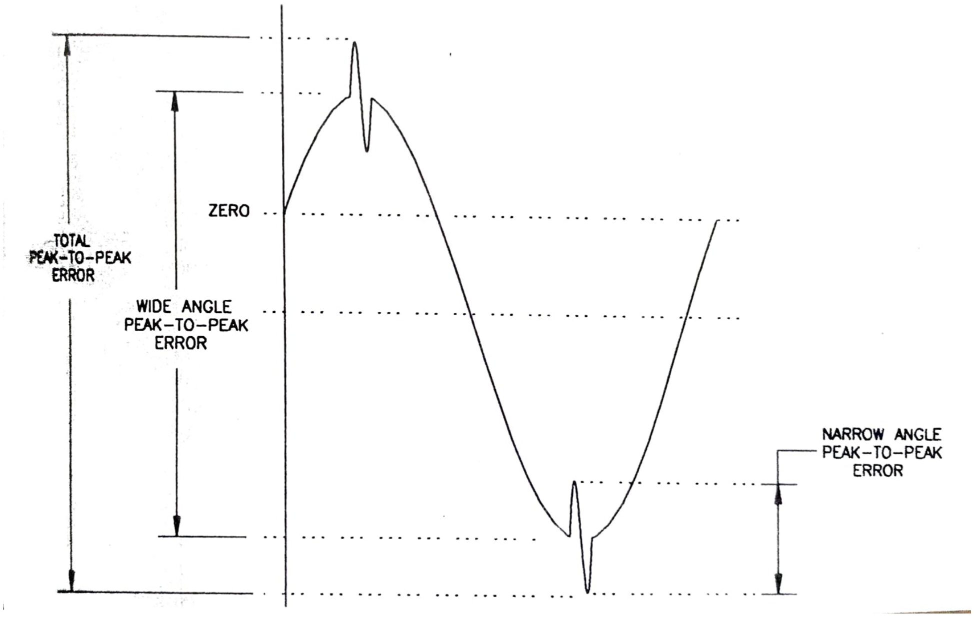


Figure 4.1: Typical error plot of an optical encoder

the stator pattern axis. This inaccuracy appears as a sinusoidal accuracy curve, often with harmonics. If the instrument is repeatable, the accuracy curve closes at $0°$ and $360°$, indicating the instrument will rotate back to the same position.

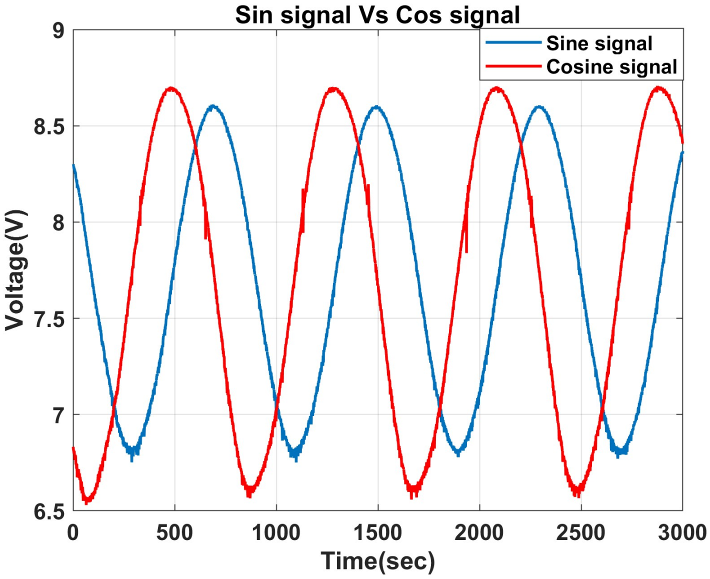


Figure 4.2: Eccentricity error in optical encoder

The Fig 4.2 represents the effects of eccentricity error on the phase difference and amplitude difference between two signals, specifically sine and cosine waves. Eccentricity error refers to a type of error commonly encountered in rotary encoders, where the center of rotation of the encoder disk does not perfectly coincide with the axis of rotation.

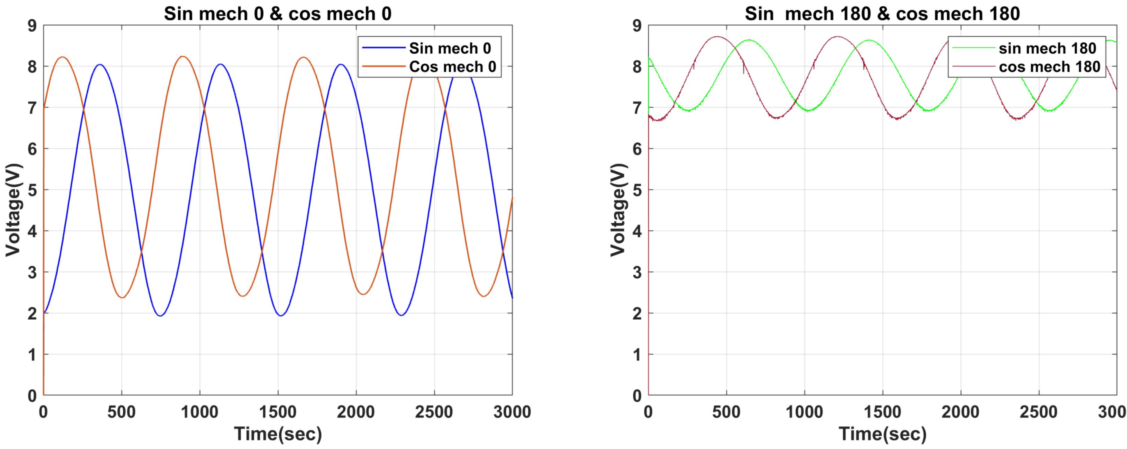
4.2.2 Narrow Angle Error

The main cause of narrow-angle mistakes is the sine and cosine encoder signals, which are utilised to create finer resolution bits. To achieve high fine-bit resolution and precision, sine and cosine signals must be spectrally pure and perfectly matched in terms of their phase, amplitude, frequency, and dc offset. "Narrow-angle errors" are the distortions that affect these sine and cosine signal parameters. For better resolution, the upper and lower half cycles of the sinusoidal signals generated by the encoder must be smooth and symmetrical.

4.2.3 Classification of Narrow angle error

1. **Offset Error:**

   An offset or bias in the encoder's output signal, which can result in inaccuracies in position measurement. Offset error can occur due to various factors, such as manufacturing tolerances, misalignment of disk between reticule, variations in sensor sensitivity, or electrical noise. These factors can introduce a systematic error in the encoder output, causing a consistent deviation from the actual position. Offset error is typically expressed as an angular or linear displacement and can be positive or negative, depending on the direction of the error.



(a) (b)

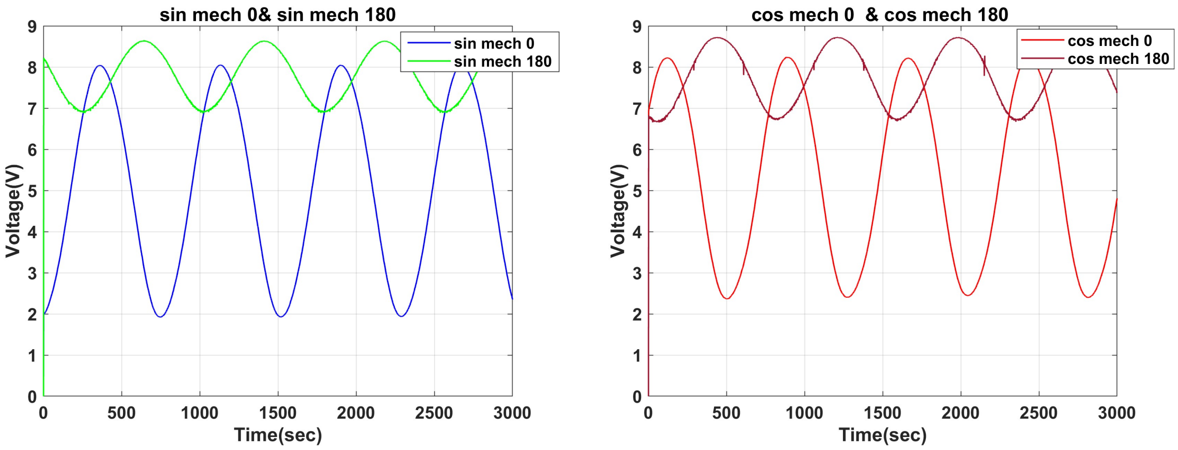
Figure 4.3: Offset error of (a) Sin/ Cos signal at 0° **;** (b) Sin/ Cos signal at 180° .

2. **Gain Error:** Gain error refers to the difference in amplitude between the sine and cosine signals in an encoder system, which results in an error in determining the position. In

an ideal scenario, the sine and cosine wave forms generated by the encoder should have equal amplitudes to accurately represent the position information. However, due to various factors, the amplitudes of these wave forms can deviate from their intended values, leading to a gain error.

When there is a gain error, the amplitudes of the sine and cosine signals are unequal. This discrepancy introduces a distortion in the waveform, which affects the accuracy of the position measurement. The magnitude of the gain error is determined by the difference in amplitudes between the sine and cosine signals.

The gain error can arise from several sources. It can be caused by imperfections in the encoder's circuitry, such as variations in amplifier gain or non-linearities in signal processing components. Manufacturing tolerances and variations in the components used in the encoder can also contribute to gain errors. Environmental factors like temperature fluctuations or electromagnetic interference may further affect the amplitude balance between the sine and cosine signals.



(a)

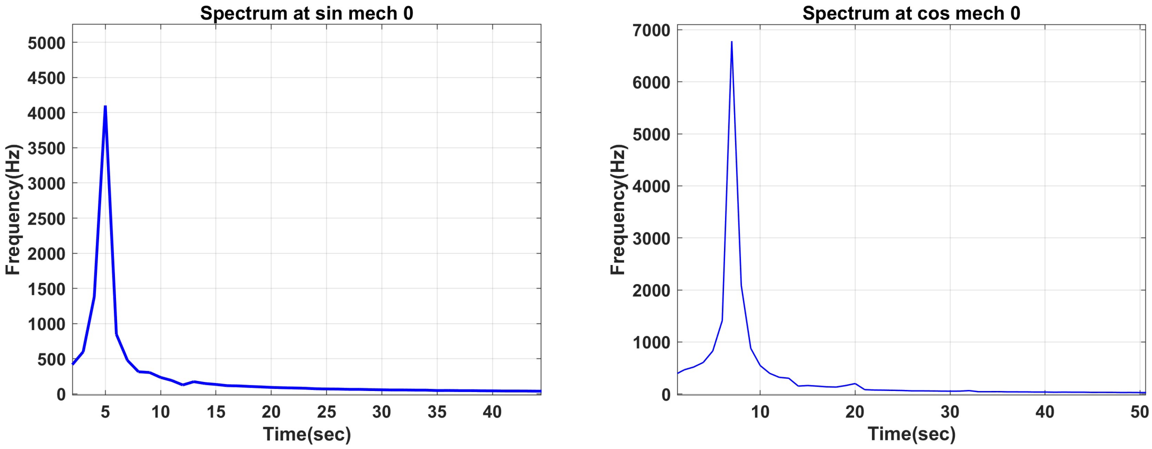
(b)

Figure 4.4: Gain error of (a) Sin signal at 0° & 180°; (b) Cos signal at 0° & 180° .

3. **Spectral Error:** An optical encoder's spectral error is defined as a deviation or distortion from the frequency spectrum of the encoder's output signals. The spectral purity and integrity of the signals the encoder produces are impacted by this particular form of error.

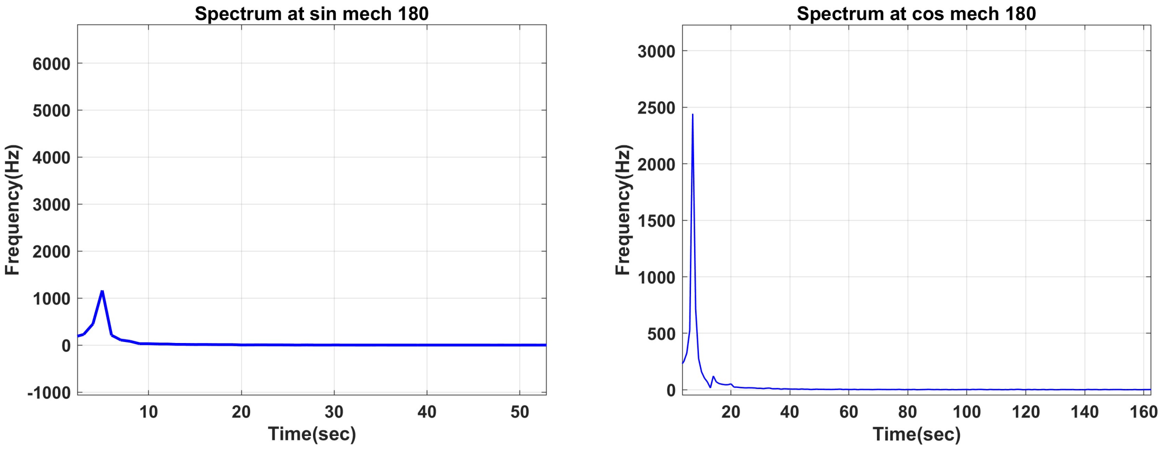
   The encoder produces signals, such as sine and cosine waves, which are used to determine the position or angular displacement of the encoder shaft. These signals are typically periodic and should ideally have a clean and well-defined frequency spectrum. However, spectral error occurs when there are deviations or irregularities in the frequency content of these signals.

Spectral error can result from various factors, harmonic distortions, noise, interference, and frequency-dependent response characteristics of the encoder components. These factors can introduce additional frequency components or distort the existing frequency components of the signals, leading to spectral errors.



(a) (b)

Figure 4.5: (a)Spectrum of Sin signal at 0° **;** (b)Spectrum of Cos signal at 0°



(a) (b)

Figure 4.6: (a)Spectrum of Sin signal at 180° **;** (b)Spectrum of Cos signal at 180° .

4.3 ERROR SOURCES

4.3.1 Wide Angle Error Sources

Wide-angle error arises primarily due to the misalignment of the rotational axis of the code pattern in relation to the spindle's axis of rotation in an encoder. If the code disc's pattern is mounted off-center, it leads to wide-angle error. Similarly, even if the code disc is mounted perfectly, but the code pattern is poorly printed, the same error occurs.

Different vendors employ various methods for disc centering. Some vendors utilize electrical techniques that can achieve results comparable to the non-repeatable error of the spindle. Other vendors rely on optical or mechanical methods, which are less precise. The bearing assembly technique also plays a crucial role. Most encoders use high-quality ball bearings like ABEC 5 or better, or air bearings. During assembly, it is important to match the eccentricities of both the outer and inner races of the bearing. The preload and spacing selected for the bearing also affect the accuracy of the encoder when under load.

Not all vendors have the same code-disc printing capabilities. Some vendors outsource the generation of masters to external facilities. The most common printing method for disc masters is the step-and-shoot method, which involves creating a high-resolution master or reticule for one segment of the disc and repetitively printing it on the disc. However, few facilities possess the mechanical and optical stability required to perform this step-and-repeat process without introducing errors. These errors occur at step and repeat resolutions, such as 12, 24, or 36 cycles per turn. Some low-resolution vendors even use an X-Y raster scan method to generate masters, resulting in errors of two or four cycles per turn. A few vendors employ more advanced methods to directly generate the code pattern. For instance, one manufacturer images each track directly on the rotating code disc, ensuring that the center of the code pattern remains stable and there are no discontinuities that need to be compensated for in the electronics.

4.3.2 Narrow Angle Error Sources

In most cases, a combination of sine and cosine waveforms is utilized to generate high-resolution bits, and resolver techniques are employed to convert these waveforms into position information. So, the error sources we talked about earlier affect all of these methods, including issues with spectral purity and the alignment of sine and cosine waves in terms of phase, amplitude, and DC offset. In encoder systems, it is common to aim for a 1% matching tolerance for amplitude and DC offset, while phase is typically set at 90 degrees with a deviation of ± 5 ° or less.

4.4 FINE ANGLE & COARSE ANGLE ERROR

In optical encoders, the errors that occur in the fine bits and coarse bits are commonly referred to as fine angle error and coarse angle error, respectively.

Fine angle error specifically pertains to the inaccuracies or deviations in the high-resolution bits of the encoder. These bits are derived from the sine and cosine signals, which are used to interpolate and achieve finer angular resolution. Fine angle error can arise due to various factors, such as signal processing limitations, noise in the signal generation, or imperfections in the encoder components. It affects the precision and accuracy of the high-resolution output and can result in positional errors in the measured values.

On the other hand, coarse angle error relates to the errors present in the lower-resolution or coarse bits of the encoder. These bits are typically obtained directly from the output of the photodetectors, which detect the encoded patterns on the disk Coarse angle error can arise due to mechanical tolerances, alignment issues, variations in the aperture sizes, or inconsistencies in the disc or reticule design. It affects the accuracy and repeatability of the coarse position measurements and can introduce systematic errors in the encoder's output.

4.5 ANALYSIS OF ERRORS IN FINE & COARSE BITS

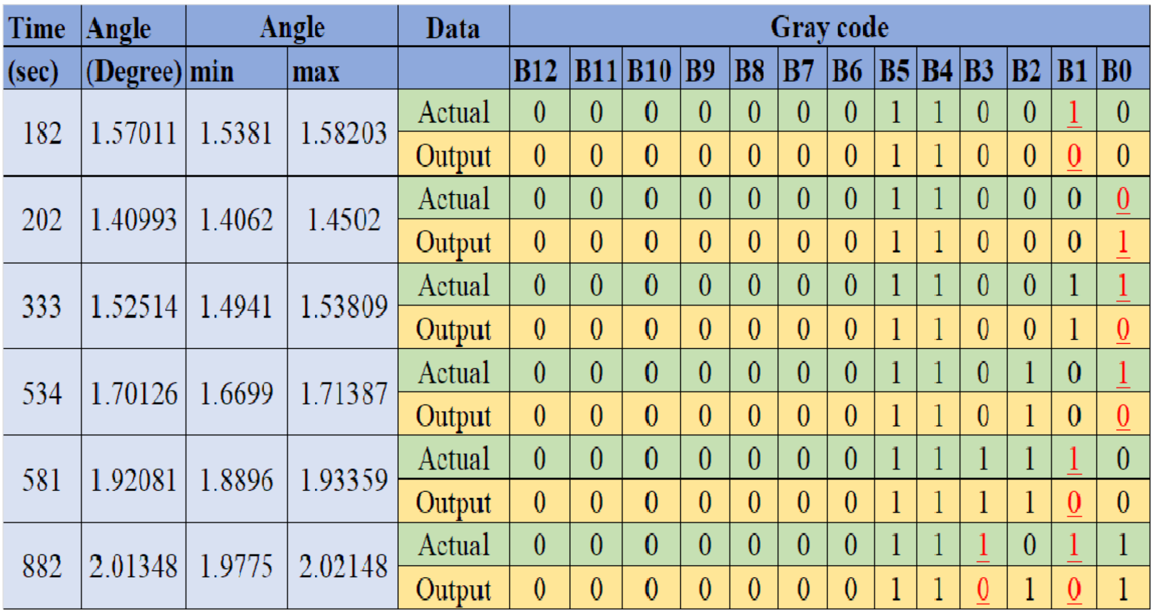
4.5.1 Methods to identify errors in Coarse bits

1. **Method 1: Look-up table**

   In the LUT (Look-Up Table) method for error analysis in optical encoders, the output bits of the encoder are compared with a pre-defined gray-coded LUT (Look-Up Table). The purpose of this comparison is to analyze and identify any errors or discrepancies in the output bits.

   The grey-coded LUT contains the expected sequence of grey-coded bits for each possible position of the encoder. By repeating the comparison of the actual output bits with the corresponding bits in the LUT, it is possible to determine if there are any errors in the encoded position.

Fig 4.7 shows some examples of LUT analysis, When the output bits deviate from the expected values in the LUT, it indicates that an error has occurred in the data. The specific error pattern observed in the output bits can provide valuable information about the type and magnitude of the error. This information can be used for error detection, error correction, or further analysis of the encoder's performance.



Time	Angle	Angle		Data	Gray code												
(sec)	(Degree)	min	max		B12	B11	B10	B9	B8	B7	B6	B5	B4	B3	B2	B1	B0
182	1.57011	1.5381	1.58203	Actual	0	0	0	0	0	0	0	1	1	0	0	1	0
				Output	0	0	0	0	0	0	0	1	1	0	0	0	0
202	1.40993	1.4062	1.4502	Actual	0	0	0	0	0	0	0	1	1	0	0	0	0
				Output	0	0	0	0	0	0	0	1	1	0	0	0	1
333	1.52514	1.4941	1.53809	Actual	0	0	0	0	0	0	0	1	1	0	0	1	1
				Output	0	0	0	0	0	0	0	1	1	0	0	1	0
534	1.70126	1.6699	1.71387	Actual	0	0	0	0	0	0	0	1	1	0	1	0	1
				Output	0	0	0	0	0	0	0	1	1	0	1	0	0
581	1.92081	1.8896	1.93359	Actual	0	0	0	0	0	0	0	1	1	1	1	1	0
				Output	0	0	0	0	0	0	0	1	1	1	1	0	0
882	2.01348	1.9775	2.02148	Actual	0	0	0	0	0	0	0	1	1	1	0	1	1
				Output	0	0	0	0	0	0	0	1	1	0	1	0	1

Figure 4.7: LUT Analysis

2. **Method 2: Fine Rollover & Coarse correction** The Fine Rollover and Coarse Correction method is a technique used to identify errors in the fine bits, coarse bits, or both in an optical encoder. The procedure for checking the error typically involves comparing the output angle obtained from both the fine and coarse measurements with the original hex data or text data. Here is a step-by-step outline of the procedure:

    (a) Obtain the output angle from the fine bits of the encoder. This can be done by reading the fine bit values and converting them into an angle measurement using the appropriate decoding method.

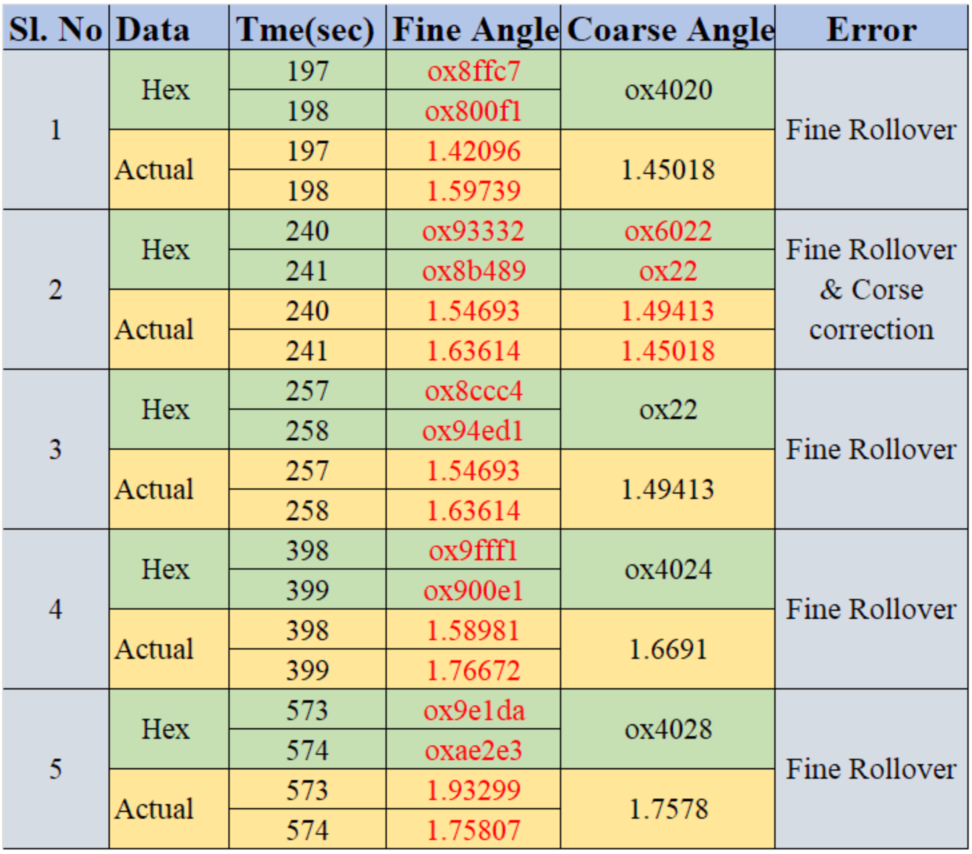
    (b) Obtain the output angle from the coarse bits of the encoder. Similarly, read the coarse bit values and convert them into an angle measurement.

(c) Compare the output angle obtained from the fine bits with the original hex data or text data that represents the expected angle. If there is a significant discrepancy between the measured angle and the expected angle, it indicates an error in the fine bits.

(d) Similarly, compare the output angle obtained from the coarse bits with the original hex data or text data. If there is a significant difference between the measured angle and the expected angle, it indicates an error in the coarse bits.

(e) If there are errors in both the fine and coarse measurements, it suggests that there may be a combination of errors affecting both sets of bits.

By comparing the output angles with the original data, identify whether the error lies in the fine bits,coarse bits, or both. This information can then be used to apply appropriate correction techniques, such as rollover compensation or interpolation, to improve the accuracy of the angle measurement. Here is an example Fig 4.8 showing the output angle compared with the text and hex data to identify whether it is a fine or coarse bit error.



Sl. No	Data	Tme(sec)	Fine Angle	Coarse Angle	Error
1	Hex	197	ox8ffc7	ox4020	Fine Rollover
		198	ox800f1		
	Actual	197	1.42096	1.45018	
		198	1.59739		
2	Hex	240	ox93332	ox6022	Fine Rollover & Corse correction
		241	ox8b489	ox22	
	Actual	240	1.54693	1.49413	
		241	1.63614	1.45018	
3	Hex	257	ox8ccc4	ox22	Fine Rollover
		258	ox94ed1		
	Actual	257	1.54693	1.49413	
		258	1.63614		
4	Hex	398	ox9fff1	ox4024	Fine Rollover
		399	ox900e1		
	Actual	398	1.58981	1.6691	
		399	1.76672		
5	Hex	573	ox9e1da	ox4028	Fine Rollover
		574	oxae2e3		
	Actual	573	1.93299	1.7578	
		574	1.75807		

Figure 4.8: Fine rollover & Coarse Correction Analysis

4.6 REFERENCE VALUE ANALYSIS

4.6.1 Testing 0 bit reference changes

The purpose of this testing is to determine the optimal reference voltage for the lower bits in an encoder. By comparing the V_{PK} values obtained for different reference voltages, we can identify the reference voltage that yields the best performance for the lower bits. In the provided data, the V_{PK} values corresponding to the 0.75 V reference voltage are consistently higher than the values for the other reference voltages. This indicates that the 0.75 V reference voltage is more suitable for achieving accurate and reliable measurements for the lower bits. Therefore, based on this testing, it can be concluded that the 0.75 V reference value is the preferred choice for the reference voltage of the lower bits in the encoder.

Table 4.1: Comparison of V_{PK} Values for Different Reference Voltages

V_{ref}	V_{PK}	V_{dc}	$V_{PK\text{-}PK}$
0	1.624	0.47	1.152
0.75	1.632	0.464	1.168
0.6	1.624	0.472	1.152
0.8	1.624	0.472	1.152
1	1.1616	0.480	1.136
1.2	1.624	0.480	1.144

4.7 SUMMARY

This chapter explores errors in optical encoders, categorized into wide angle errors and narrow angle errors. Wide angle errors are caused by uncertainties in alignment between stator pattern axis and spindle axis of rotation, which can be minimized through mechanical assembly techniques and measuring eccentricity. Narrow angle errors are mainly associated with sine and cosine encoder signals, which can be attributed to distortions in spectral purity and matching of signals' phase, amplitude, frequency, and dc offset. The smoothness and symmetry of sinusoidal signals also impact resolution improvement. Two methods are discussed for identifying errors in fine bits and coarse bits: using a Look-Up Table (LUT) and Fine Rollover and Coarse Correction method.

Testing of bit 0 is also explored, focusing on finding the reference voltage for lower bits. The conclusion is that a reference voltage of 0.75 V performs better than other values, suggesting improved accuracy for lower bits.

Overall, this chapter offers valuable insights into understanding and mitigating errors in optical encoders, identifying fine bits and coarse bits errors, and conducting testing to determine the optimal reference voltage for lower bits.

Chapter 5

OPTICAL ENCODER ACCURACY ENHANCEMENT TECHNIQUE

5.1 OVERVIEW

This chapter discusses advanced techniques for error analysis and signal processing in optical encoders, including the Arc-Tan method, bias normalization, and Lissajous plot. The Arc-Tan method extracts precise angular information from encoder signals, transforming them into accurate angle representations. Bias normalization compensates for inherent biases in encoder output, improving accuracy and resolution. The chapter explores various bias normalization approaches and their effectiveness in reducing errors. Lissajous plots provide insights into the phase relationship, amplitude balance, and linearity of encoder signals, and their implications for error detection and correction. These techniques enhance accuracy, resolution, and error detection capabilities, ultimately improving the performance and reliability of optical encoders in various applications.

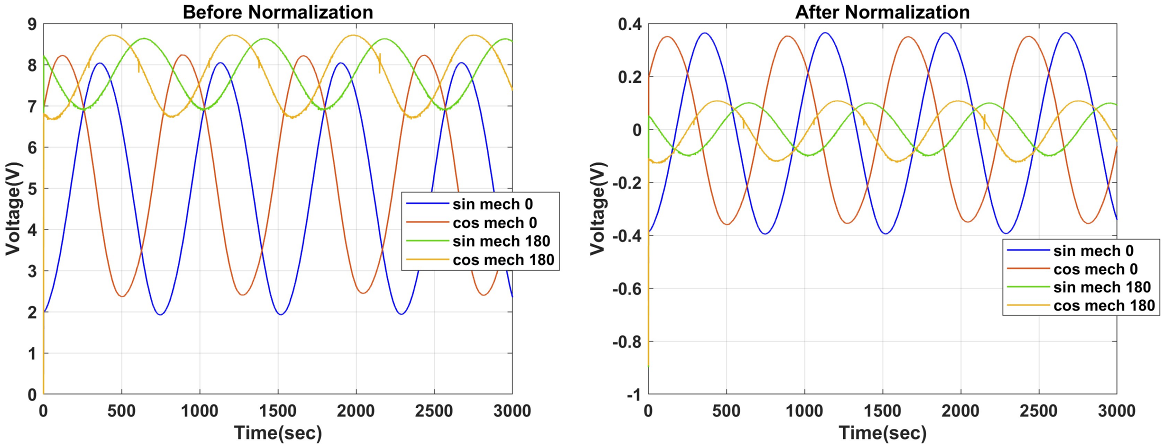
5.2 BIAS NORMALIZATION

Bias normalization is a technique used to improve the accuracy and precision of the output sine/cosine signals in optical encoders. It involves adjusting the signals by adding or subtracting a bias value to align them with the expected ideal values.

The purpose of bias normalization is to eliminate systematic errors or deviations in the signals that may arise due to factors such as offset and gain errors. These errors can affect the accuracy and reliability of the encoder measurements. By applying appropriate bias values, the output signals can be shifted or calibrated to match the desired reference values.

The bias value is determined through careful calibration and characterization of the encoder system. This may involve using reference sources or known reference values to establish the correct bias offset. The bias value can be applied to both the sine and cosine signals to ensure that they are normalized and free from any systematic errors.

The bias normalization technique plays a crucial role in achieving accurate and reliable measurements in optical encoders. By normalizing the output signals with bias values, the encoder's performance can be enhanced, leading to improved overall accuracy.



(a) (b)

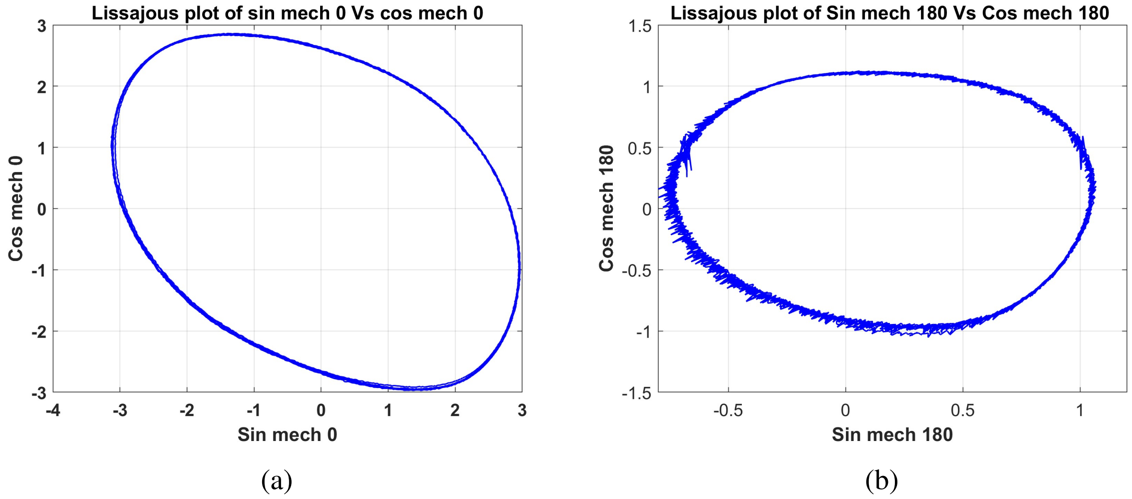
Figure 5.1: Encoder output sin/cos signal (a) Before Normalization; (b) After Normalization.

After the normalization process, the output signals from an optical encoder can be further analyzed using a Lissajous plot. A Lissajous plot is a graphical representation of the relationship between two sinusoidal signals. In the context of optical encoders, the Lissajous plot is used to visualize the phase relationship between the normalized sine and cosine signals.

The Lissajous plot serves as a visual tool to assess the quality and accuracy of the encoder signals. It provides valuable insights into the performance and integrity of the encoder system. By examining the Lissajous plot, engineers can make adjustments or corrections to improve the signal quality and ensure more precise position measurements from the optical encoder.

Ideally, when the encoder is functioning correctly and there are no errors, the Lissajous plot will form a perfect circle. This indicates that the phase relationship between the sine and cosine signals is accurate, and the encoder is providing reliable position information.

However, in real-world scenarios, there can be errors or distortions present in the encoder signals, which can lead to deviations from the ideal Lissajous plot shown in Fig 5.2. These errors can arise from factors such as noise, interference, signal irregularities, or inaccuracies in the encoder components.



(a)

(b)

Figure 5.2: Lissajous Plot Before Normalization (a) Sin/cos signal at 0°**;** (b) Sin/cos signal at 180°.

By analyzing the Lissajous plot, it is possible to identify and diagnose errors in the encoder signals. Deviations from the ideal circle shape, such as asymmetry, distortion, or elliptical deformation, can indicate the presence of errors in the encoder output.

5.3 ARC-TAN METHOD

The arc-tan method is a signal processing technique used in optical encoders to determine the position or angle of rotation based on the output signals. It involves calculating the arctangent (inverse tangent) of the ratio between the sine and cosine signals generated by the encoder.

In optical encoders, the sine and cosine signals are typically produced by a sensor as the encoder's shaft rotates. These signals are sinusoidal in nature and have a phase shift relative to each other, which corresponds to the angle of rotation. By using the arc-tan method, the phase shift between the sine and cosine signals can be measured and converted into an angle value.

The arc-tan method takes advantage of the trigonometric relationship between the sine and cosine functions. By calculating the arctangent of the ratio of the sine and cosine signals, the angle can be obtained. This method provides a convenient and efficient way to determine the

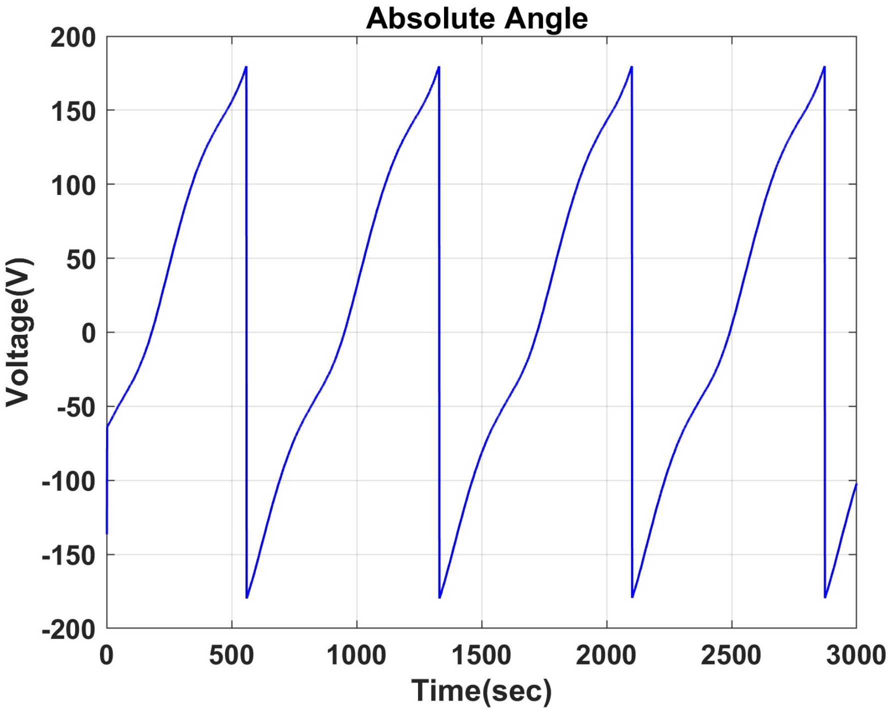


Figure 5.3: Absolute Angle

position or angle of rotation in optical encoders. To find the value of absolute angle "θ" by using the equation,

$$\theta = tan^{-1}\left[\frac{sin\theta}{cos\theta}\right] \tag{5.1}$$

5.4 SUMMARY

The chapter discusses the arc-tan method, which determines the angle of rotation based on encoder sine and cosine signals, enabling accurate angular measurements. It also discusses normalisation of encoder output signals using bias values, which eliminates systematic errors and improves measurement accuracy. The chapter also discusses the use of Lissajous plots, which visually represent the phase relationship between normalised sine and cosine signals, allowing engineers to identify errors and optimize performance. These techniques are crucial for understanding and improving the accuracy of optical encoder measurements.

Chapter 6

NONIOUS ENCODER

6.1 OVERVIEW

The Nonious encoder is a precision measurement device with two tracks, the master track and the Nonious track. To ensure accuracy, various error analysis techniques are employed. Orthogonality analysis evaluates the phase difference between the master and Nonious tracks, while Lissajous plot assesses the performance. Amplitude mismatch analysis examines the consistency of signal amplitudes between the master and Nonious tracks, preventing inaccuracies in measurement results. Spectral analysis examines frequency characteristics, detecting harmonics, noise, and other errors that may affect the encoder's accuracy. By addressing these errors, the encoder's precision and reliability can be enhanced, ensuring accurate and trustworthy measurements in various applications.

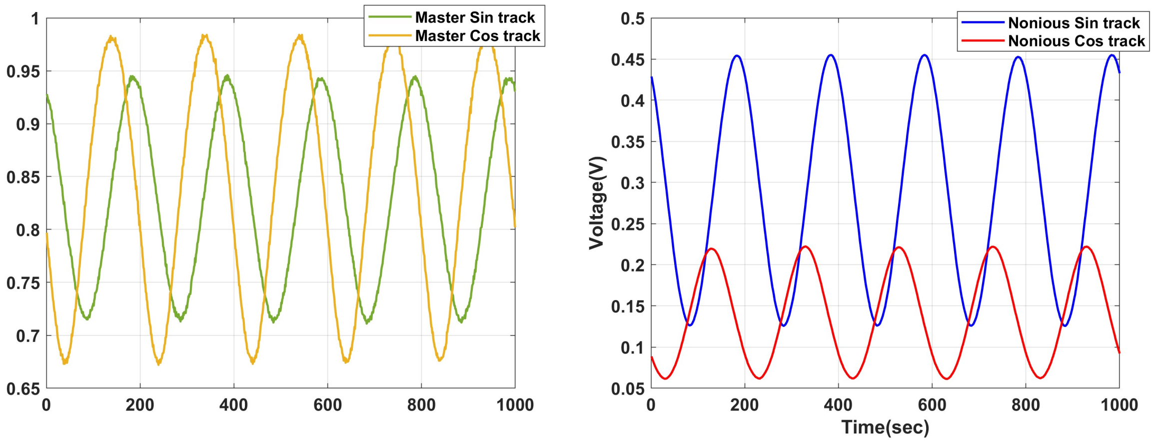
6.2 CONFIGURATION

A Nonious encoder is a type of encoder that incorporates two tracks: a master track and a Nonious track. The master track usually consists of a higher number of divisions, and the Nonious track has fewer divisions compared to the master track by one resolution step.

Nonious encoder having a master track with 2048 divisions and a Nonious track with 2047 divisions, the resolution of the encoder can be calculated by dividing 360 degrees (a complete circle) by the number of divisions on the master track.

$$\begin{aligned} \text{Resolution} &= 360 \text{ degrees}/2048 \text{ divisions} && (6.1) \\ &= 0.17578125 \text{ degrees per division} && (6.2) \end{aligned}$$

Nonious encoders rotate at a rate of 0.1757 degrees per second in the clockwise direction. The output of both the master and nonious track is given in the Fig 6.1. The sampling rate is 5 milliseconds.



(a)

(b)

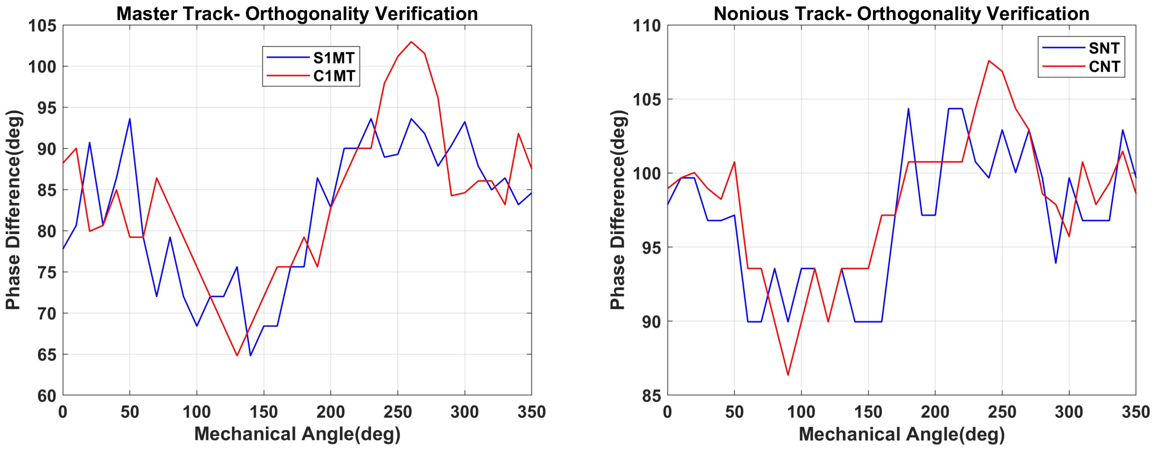
Figure 6.1: Nonious encoder output of (a)Master Track**;** (b) Nonious Track.

The figure provided consists of two tracks: Fig 6.1(a) represents the master track, displaying sin and cos signals, while Fig 6.1(b) represents the nonious track, also displaying sin and cos signals. Upon observing the figure, it becomes evident that the output signal contains various errors.

6.3 ERROR ANALYSIS

6.3.1 Orthogonality Verification

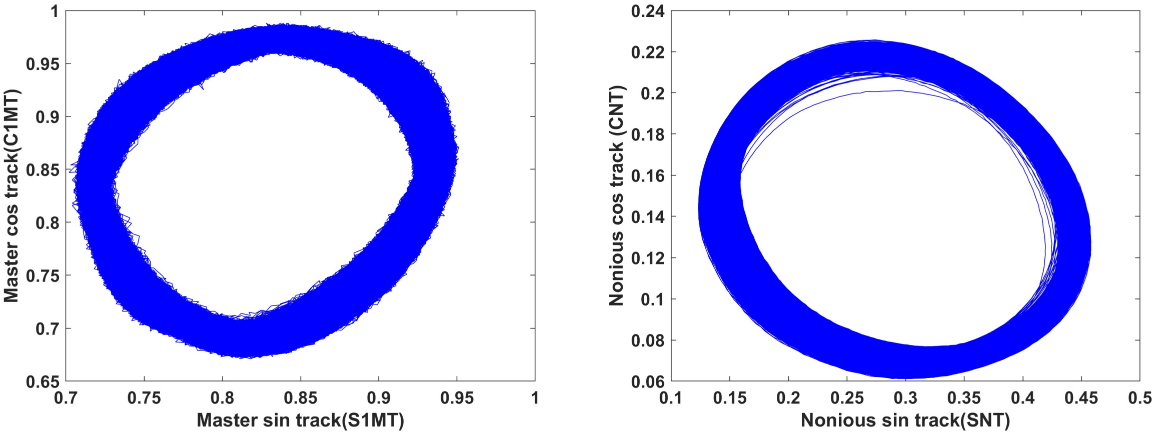
Orthogonality verification analysis is a process used to assess the degree of orthogonality between two signals. It refers to evaluating the orthogonality of the sine and cosine signals generated by the encoder. Orthogonal signals are independent and mutually perpendicular to each other. In an encoder, the sine and cosine signals are ideally orthogonal, meaning they are 90 degrees out of phase and have no correlation or interference between them. The orthogonality of these signals is crucial for accurate angle measurement and precise position determination.



(a) (b)

Figure 6.2: Phase difference at peak and zero crossing of (a)Master Track; (b) Nonious Track.

To perform an orthogonality verification analysis, the sine and cosine signals are analysed using various techniques. One commonly used method is the Lissajous plot, which visually represents the relationship between the two signals. A Lissajous plot is a graph where the amplitude of the cosine signal is plotted against the amplitude of the sine signal.



(a) (b)

Figure 6.3: Before normalization- Lissajous plot of (a)Master Track; (b) Nonious Track.

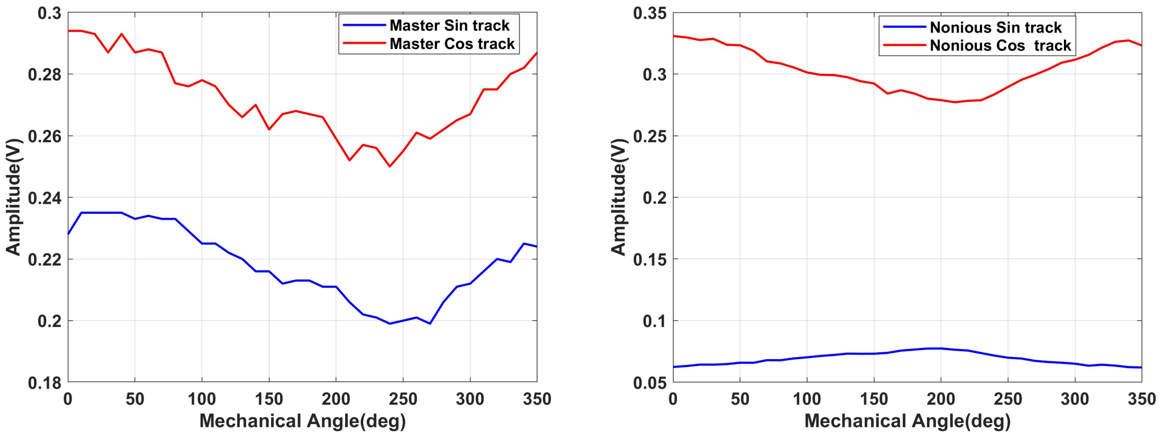
During phase difference analysis, the encoder outputs, i.e., the master track and the Nonious track, are compared to determine the phase difference between them. This can be done by analyzing the wave forms of the two tracks. One common approach is to calculate the phase shift between the two tracks at specific points, such as at zero crossings or at peak amplitudes. The phase difference is obtained by measuring the time delay or angle between the corresponding points on the wave forms. If the phase difference between the master track and the Nonious track deviates from the ideal $90°$, it indicates a lack of orthogonality. This deviation can be quantified as the phase error.

6.3.2 Amplitude Mismatch

Amplitude mismatch analysis is a method used to evaluate the differences in signal amplitudes between two signals.

In an ideal scenario, the master track and the Nonious track should have equal and consistent amplitudes. However, in practical situations, variations in amplitudes can occur due to factors such as manufacturing tolerances, signal distortions, or mechanical imperfections.

During amplitude mismatch analysis, the amplitude values of the master track and the Nonious track are compared to determine any differences or inconsistencies. This can be done by measuring the peak amplitudes or analyzing the average amplitudes of the two signals.



(a) (b)

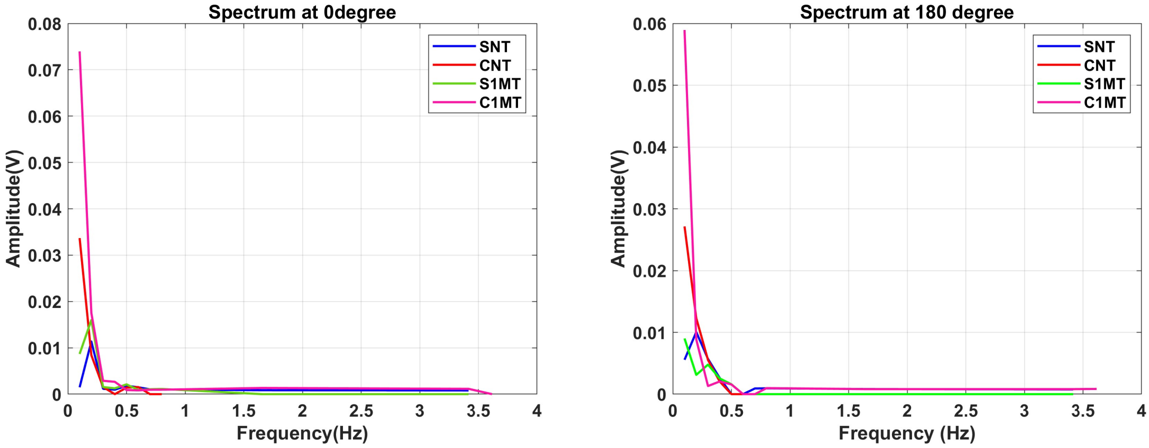
Figure 6.4: Amplitude variation of sin & cos (a)Master Track; (b) Nonious Track.

6.3.3 Spectral Analysis

Spectral analysis is a technique used to analyze the frequency content of a signal or data set. In the encoder analysis, spectral analysis is employed to examine the frequency components present in the encoder's output signals.

By performing spectral analysis on the encoder's signals, the frequency components and their respective magnitudes can be identified. This analysis provides insights into the signal's frequency distribution, the presence of any harmonics or noise, and the overall spectral characteristics.

The process of spectral analysis involves applying mathematical algorithms such as Fourier transform or wavelet transform to convert the time-domain signal into the frequency-domain representation. This allows for a detailed examination of the signal's frequency content.



(a)

(b)

Figure 6.5: Spectal analysis of both master and nonious track at(a)Zero degree**;** (b) 180 degree.

The results of spectral analysis are often represented using a frequency spectrum, which is a graphical plot showing the magnitude of each frequency component present in the signal. The spectrum can be visualized as a histogram or a line plot, where the x-axis represents the frequency and the y-axis represents the magnitude.

Spectral analysis is valuable in encoder analysis as it helps in assessing the signal quality, identifying any unwanted frequency components or noise, and verifying the presence of desired frequency components. It allows for the detection of anomalies, distortions, or interference that may affect the accuracy and reliability of the encoder's measurements.

In the context of error analysis, spectral analysis can be used to identify any spectral errors or deviations in the encoder's output signals. This includes examining the spectral purity of the signal, checking for the presence of harmonics or spurious frequencies, and evaluating the overall frequency response of the encoder.

By analyzing the spectral characteristics of the encoder's signals, potential sources of error or distortion can be identified. This information can then be used to optimize the encoder's design, improve signal conditioning techniques, or implement corrective measures to minimize spectral errors.

6.4 SUMMARY

The Nonious encoder is a two-track encoder with higher resolution, allowing for precise measurements. Error analysis, such as orthogonality verification, Lissajous plot analysis, amplitude mismatch analysis, and spectral analysis, are crucial for evaluating the encoder's performance and accuracy. Orthogonality verification assesses the phase difference between the master and Nonious tracks, while Lissajous plot analysis observes deviations from the ideal pattern. Amplitude mismatch analysis evaluates the consistency of signal amplitudes, while spectral analysis examines frequency content to identify harmonics, noise, and other errors. By addressing these issues, the encoder's precision can be improved, ensuring reliable and accurate measurements.

Chapter 7

COMPENSATION TECHNIQUES

7.1 OVERVIEW

In the field of optical encoders, high accuracy is crucial for precise position sensing. Techniques like normalization, linear interpolation, harmonic approximation, and ratiometric technique are employed to reduce errors and enhance accuracy. Normalization removes bias and ensures consistency in encoder signals, while linear interpolation smooths out irregularities. Harmonic approximation analyzes repeating signals' frequencies, identifying errors and addressing them. The ratiometric technique calculates the difference between two sinusoidal signals, enhancing linearity and reducing non-linearities.

Combining these techniques effectively reduces errors in optical encoders, resulting in improved accuracy in position measurements. These techniques are essential in various applications requiring precise and reliable position sensing.

7.2 NORMALIZATION

Normalization of a Nonious encoder refers to the process of adjusting or normalising the output signals from the master and Nonious tracks to ensure accurate measurements. The normalisation process typically involves comparing the output signals from both tracks and applying correction factors or adjustments to compensate for any differences. These adjustments aim to ensure that the signals are aligned properly and that the encoder's resolution is utilised effectively.

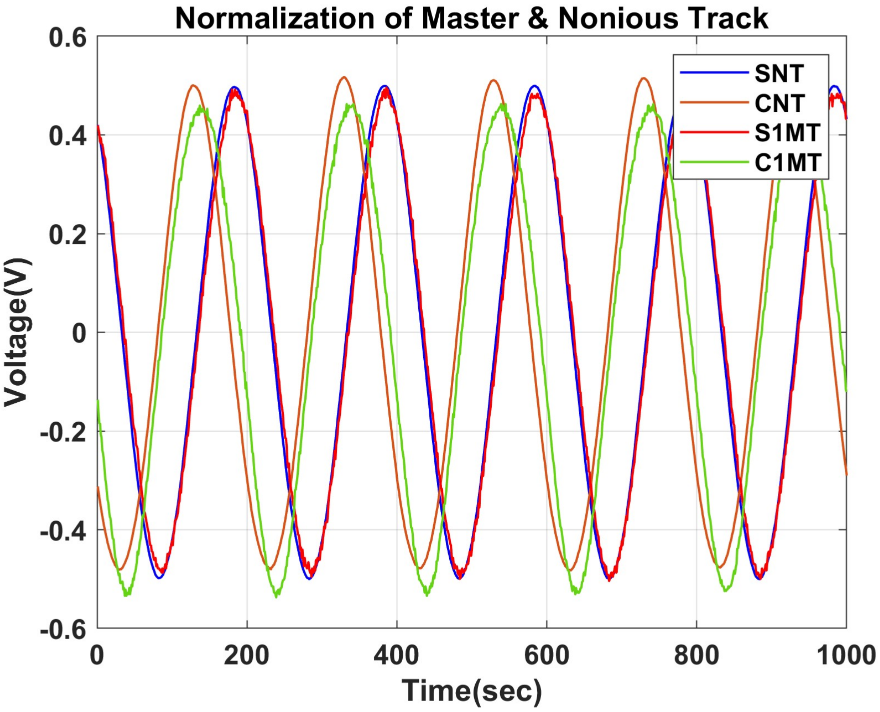
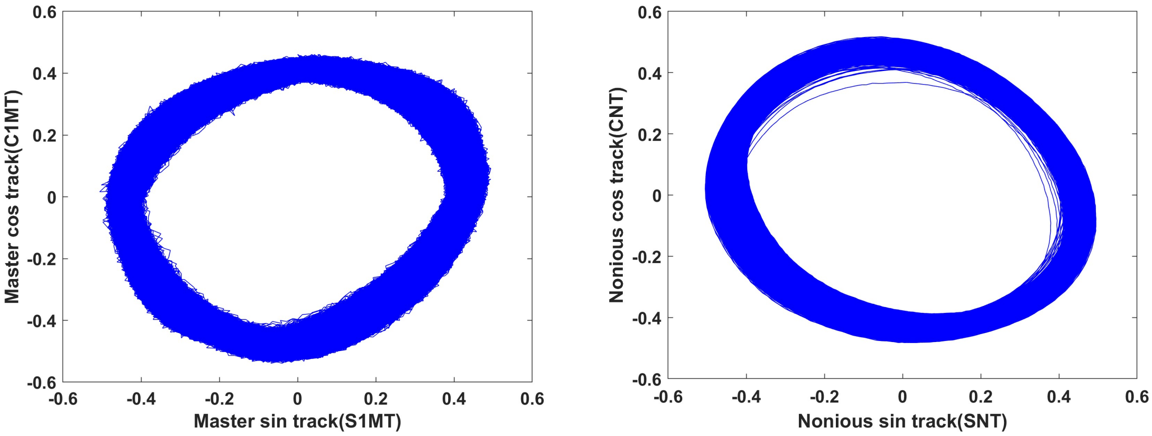


Figure 7.1: After normalization of Master and Nonious track



(a) (b)

Figure 7.2: After Normalization Lissajous Plot of (a)Master Track**;** (b) Nonious Track.

Normalisation techniques may involve mathematical calculations or algorithms to determine the necessary adjustments. This could include scaling, offsetting, or other mathematical operations to align the signals and bring them into coherence. By normalising the output signals of the Nonious encoder, the accuracy and precision of the measurements can be improved. It helps account for any discrepancies between the master and Nonious tracks, enabling more reliable and consistent readings from the encoder.

Normalization equation of nonious sine track is:

$$\text{SNT- Normalized signal} = \frac{\text{SNT}_{\text{demean}}}{\text{SNT}_{\text{range}}}$$

$$\text{SNT}_{\text{demean}} = \text{SNT} - \text{mean}(\text{SNT})$$

$$\text{SNT}_{\text{range}} = \max(\text{SNT}) - \min(\text{SNT})$$

Normalization equation of nonious cosine track is:

$$\text{CNT- Normalized signal} = \frac{\text{CNT}_{\text{demean}}}{\text{CNT}_{\text{range}}}$$

$$\text{CNT}_{\text{demean}} = \text{CNT} - \text{mean}(\text{CNT})$$

$$\text{CNT}_{\text{range}} = \max(\text{CNT}) - \min(\text{CNT})$$

Normalization equation of master sine track is:

$$\text{S1MT- Normalized signal} = \frac{\text{S1MT}_{\text{demean}}}{\text{S1MT}_{\text{range}}}$$

$$\text{S1MT}_{\text{demean}} = \text{S1MT} - \text{mean}(\text{S1MT})$$

$$\text{S1MT}_{\text{range}} = \max(\text{S1MT}) - \min(\text{S1MT})$$

Normalization equation of master cosine track is:

$$\text{C1MT- Normalized signal} = \frac{\text{C1MT}_{\text{demean}}}{\text{C1MT}_{\text{range}}}$$

$$\text{C1MT}_{\text{demean}} = \text{C1MT} - \text{mean}(\text{C1MT})$$

$$\text{C1MT}_{\text{range}} = \max(\text{C1MT}) - \min(\text{C1MT})$$

The figure includes Lissajous plots obtained after normalization. Fig 7.2(a) represents the Lissajous plot of the master track, while Fig 7.2(b) represents the Lissajous plot of the nonious track. Upon examining the figure, it becomes apparent that additional errors are present even after the normalization process.

7.3 COMPLIMENTARY METHOD

One complementary method for reducing errors in a signal is through the technique of second harmonic cancellation. This technique focuses on mitigating the presence of second harmonics, which are unwanted frequency components that can introduce distortion and affect the accuracy of the signal.

The principle behind second harmonic cancellation involves generating an anti-phase signal that is precisely aligned with the second harmonic components of the original signal. By combining the original signal and the anti-phase signal in a manner that ensures destructive interference, the second harmonics can be effectively canceled out.

To implement this technique, specialized circuitry or algorithms are utilized to identify the second harmonic frequencies and generate the corresponding anti-phase signals. These anti-phase signals are then combined with the original signal, resulting in a modified signal with reduced second harmonic content.

By reducing the presence of second harmonics, the signal becomes cleaner and closer to its intended form. This helps to enhance the accuracy and fidelity of the signal, making it more reliable for various applications such as audio reproduction, signal processing, and communications systems.

It is important to note that second harmonic cancellation is just one approach among many for reducing errors in a signal. Depending on the specific requirements and characteristics of the system, other complementary methods and techniques may also be employed to improve signal quality and mitigate errors.

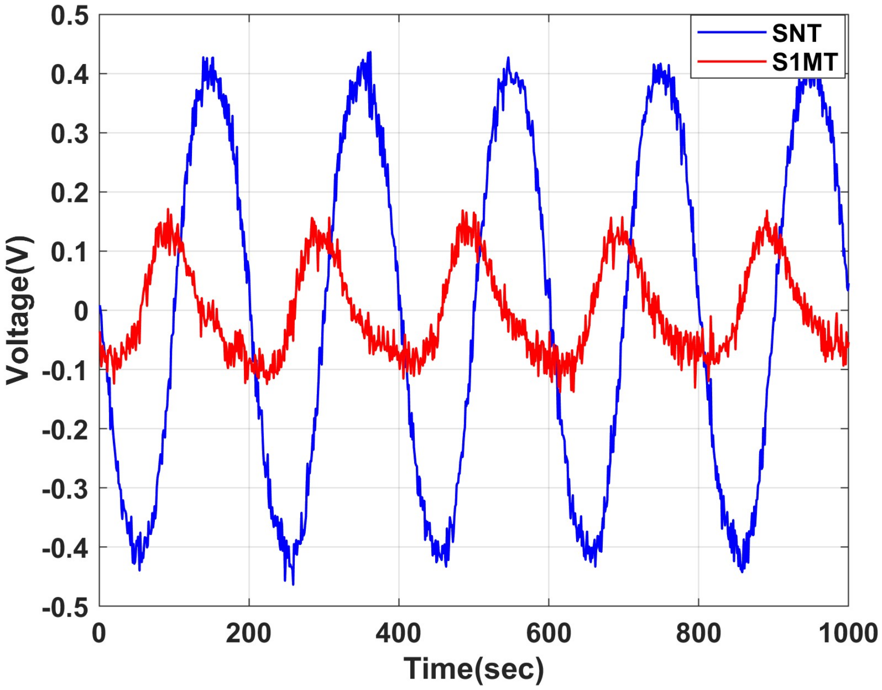


Figure 7.3: After complimentary method Sine wave signal

The complementary method refers to a specific approach or technique employed to address and minimize errors in the data or waveform. It was chosen with the intention of improving the accuracy or precision of the results.

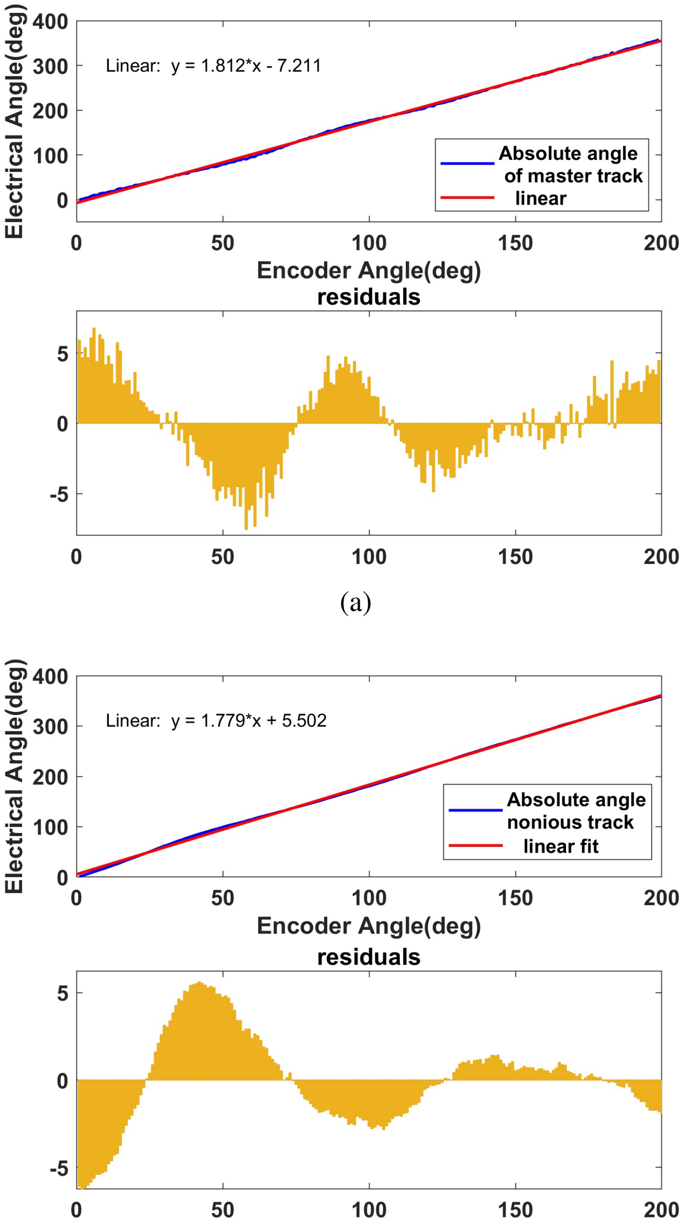
Unfortunately, based on the Fig 7.3, it becomes apparent that the complementary method did not achieve the desired outcome of error reduction. The error, which represents the discrepancy between the observed values and the expected values, remains relatively high or unchanged after applying the method.

Given the lack of success in minimizing the error through the complementary method, it becomes necessary to explore alternative methods or approaches to address and mitigate the error. It may be advisable to consider different techniques, models, or algorithms that are better suited to the specific characteristics or nature of the data, in order to achieve the desired level of error reduction.

7.4 LINEAR INTERPOLATION METHOD

The linear interpolation method involves estimating the value of an unknown data point within a range based on the known data points on either side of it. Linear interpolation can be used to determine the angle corresponding to a specific position within the range of known angles.

The process begins by obtaining a set of data points consisting of the known absolute angles and their corresponding positions. These data points are used to create a linear fit, which represents the trend or relationship between the position and the absolute angle.



(a)

(b)

Figure 7.4: Linear Fitting of the (a)Master track**;** (b) Nonious track.

To perform linear interpolation, the position of interest is identified within the range of known positions. The two data points closest to the position of interest are then selected. Using these two data points, a straight line is constructed, which represents the linear fit or trend observed in the data.

The absolute angle at the position of interest is then estimated by determining the intersection point of the straight line with the vertical line corresponding to the position of interest. This intersection point represents the interpolated absolute angle value.

Linear interpolation provides a relatively simple and efficient method for estimating unknown values within a range based on the known data points. However, it should be noted that the accuracy of the interpolation depends on the linearity and distribution of the known data points. Non-linear or unevenly spaced data points may require more advanced interpolation methods to achieve accurate results.

7.5 HARMONIC APPROXIMATION

Harmonic approximation is a technique used to analyze and correct the residual values obtained from the linear fit in absolute angle measurement. It involves decomposing the repeating signal into its constituent frequencies using a Fourier analysis or similar method.

Once the signal is decomposed into its frequencies, the correction curve is repeated after every rotation shown in Fig 7.5. By repeating the correction curve, the presence of various frequencies in the signal becomes more evident. Each frequency represents a harmonic component of the signal.

The correction curve, consisting of the harmonic components, is then used to adjust or correct the residual values obtained from the linear fit. This helps to refine the accuracy of the absolute angle measurement.

By applying harmonic approximation, the correction curve can capture and compensate for any periodic errors or deviations in the measured absolute angle. The correction curve is typically repeated periodically, ensuring that it accurately describes the frequencies present in the signal.

Using a Fourier transform, the phase and amplitude for each composing frequency of the correction curve can be determined.

$$\text{Correction amplitude} = 2 \cdot \text{abs}(\text{ff}(\text{Absolute angle})) \tag{7.1}$$

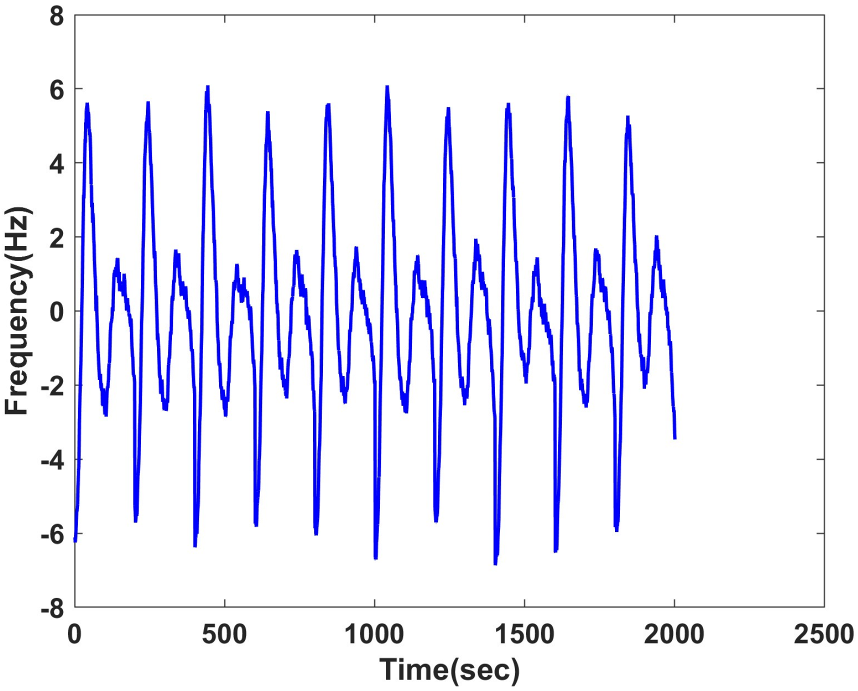


Figure 7.5: The repeated Residuals contains various frequencies

$$\text{Correction phase} = 2 \cdot \text{angle}(\text{fft}(\text{Absolute angle})) \tag{7.2}$$

In this Table 7.1, the term "harmonics" refers to the individual components of a complex waveform. Each harmonic is assigned a unique number to indicate its position within the series. The amplitude column represents the magnitude or strength of each harmonic, while the phase column signifies the relative position or angle of each harmonic within the waveform.

To determine the amplitude and phase values for each harmonic, an equation (7.1)& (7.2) is used for the computation. This equation takes into account the fundamental frequency and the waveform's characteristics, enabling the calculation of the amplitude and phase values for each individual harmonic is shown in Fig 7.6.

The waveform is represented visually when the table has been filled with the appropriate values for each harmonic. Insights into the waveform's composition and behaviour are gained by using this representation to analyse the various waveform constituents.

In some cases, due to the distinct differences in amplitude and phase among the harmonics, a technique called harmonic approximation can be employed to reduce the number of harmonics. This technique involves simplifying the waveform by approximating it with a smaller

Table 7.1: Harmonics, Amplitude & Phase data

Harmonics	Amplitude ($\circ$)	Phase (radian)
1	0.968309538	-1.96616246
2	0.138044658	2.397011643
3	3.084122695	-3.081482112
4	1.399201265	2.032917615
5	0.968367266	1.807914638
6	0.301510304	1.450899147
7	0.220209305	1.299507704
8	0.155111179	1.883454777
9	0.238345704	1.967783198
10	0.080555996	1.925498138

number of dominant harmonics, thus reducing computational complexity and data size while still preserving essential features of the original waveform.

The correction value for the n^{th} harmonic at a specific angle can be found as:

$$\text{Correction Curve} = \text{correction amplitude} \cdot (\text{no:of harmonics} \cdot \text{Absolute angle} + \text{Correction Phase}) \tag{7.3}$$

A Fig 7.7 is Correction Curve After Harmonic Approximation. In this figure, the residual range spans from -3V to 5V. After applying the harmonic approximation technique, the residual range is significantly reduced, narrowing down to nearly 0 V. This indicates that the technique effectively mitigates or diminishes the range of values in the residual waveform. The harmonic approximation technique aims to simplify the waveform by approximating it with a smaller number of dominant harmonics, reducing computational complexity and data size. This results in a more concise representation with a smaller range of values.

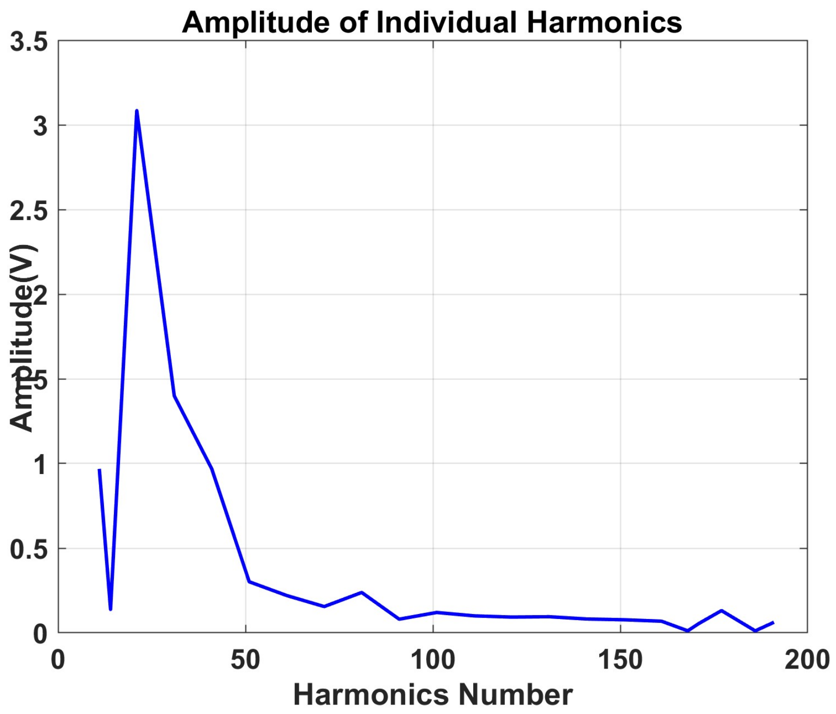


Figure 7.6: Amplitude of first residual harmonics.

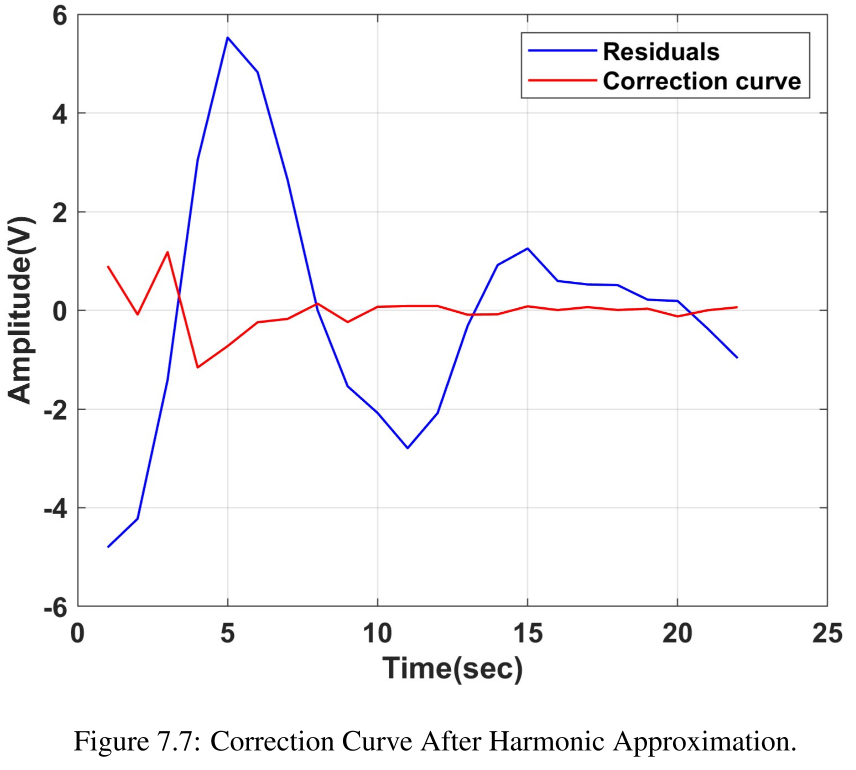


Figure 7.7: Correction Curve After Harmonic Approximation.

7.6 RATIO-METRIC TECHNIQUE

The ratio metric technique is used in the proposed scheme to improve the linearity of the output signal in optical encoders. This technique involves calculating the absolute values of two sinusoidal signals and then computing the ratio of their difference with their sum. By performing this calculation, a compensation signal is generated to enhance the linearity of the output signal. This method helps reduce non-linearities and improve the accuracy of the encoder measurements.

7.6.1 Basic principle using a ratiometric technique

Ideally, the pair of electrical signals generated by an optical encoder is described as;

For Nonious track,

$$V_{SN}(\theta) = SNT$$

$$V_{CN}(\theta) = CNT,$$

where θ is a phase angle The output signal for Nonious track:

$$V_{ON}(\theta) = \frac{|V_S(\theta)| - |V_C(\theta)|}{|V_S(\theta)| + |V_C(\theta)|} = \frac{|SNT| - |CNT|}{|SNT| + |CNT|}$$

For Master track,

$$V_{SM}(\theta) = S1MT$$

$$V_{CM}(\theta) = C1MT,$$

The output signal for Master track:

$$V_{OM}(\theta) = \frac{|V_S(\theta)| - |V_C(\theta)|}{|V_S(\theta)| + |V_C(\theta)|} = \frac{|S1MT| - |C1MT|}{|S1MT| + |C1MT|}$$

where "θ" is a phase angle

For easy calculation and analysis, we take the nonius track;

$$V_S(\theta) = SNT \tag{7.4}$$

$$V_C(\theta) = CNT \tag{7.5}$$

The output signal is;

$$V_O(\theta) = \frac{|V_S(\theta)| - |V_C(\theta)|}{|V_S(\theta)| + |V_C(\theta)|} = \frac{|SNT| - |CNT|}{|SNT| + |CNT|} \tag{7.6}$$

As depicted in Fig 7.8, it is a nearly piecewise linear signal. The pseudo-linearity of the sections of $V_{\mathrm{O}}(\theta)$ offers the prospect of the determination of the displacement using simple linear equations. We can also find that $V_{\mathrm{O}}(\theta)$ compares reasonably well with a perfect triangular waveform $PT(\theta)$ with a period of π. The waveform $PT(\theta)$ can be given by;

$$PT(\theta) = \frac{2a}{\pi}\left(\sin^{-1}(\sin\frac{2\pi}{p}\theta)\right) \tag{7.7}$$

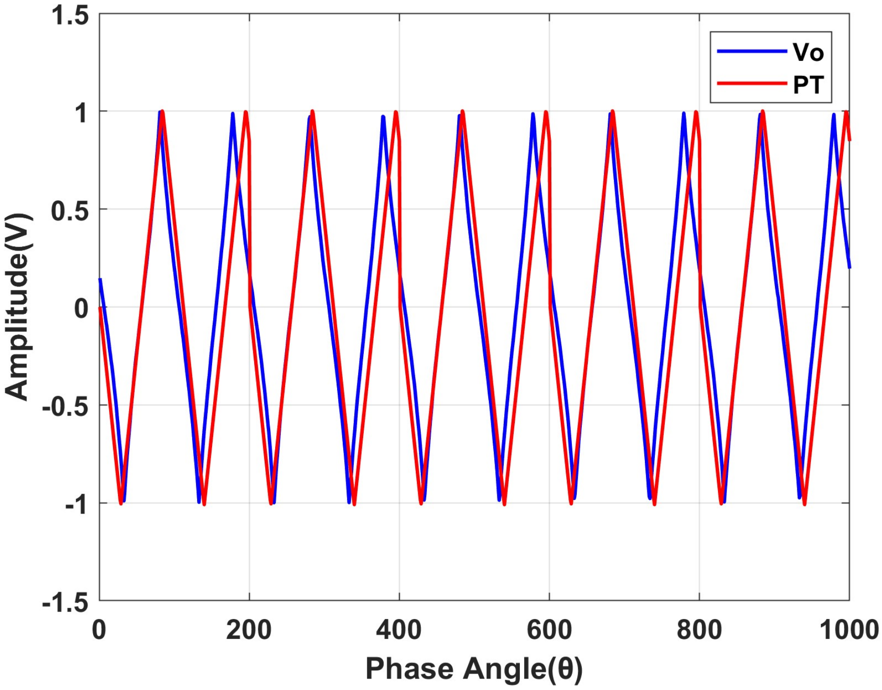


Figure 7.8: Piece-wise linear signal $V_{\mathrm{O}}(\theta)$ and the perfect triangular wave $PT(\theta)$.

The deviation of $V_{\mathrm{O}}(\theta)$ from $PT(\theta)$ is given by;

$$E_O(\theta) = V_O(\theta) - PT(\theta). \tag{7.8}$$

In order to further linearize signal $V_{\mathrm{O}}(\theta)$, a real-time compensation signal $C_{\mathrm{O}}(\theta) \approx -E_{\mathrm{O}}(\theta)$, should be constructed by a combination of the two input signals.The compensation signal $C(\theta)$ should result in a nearly perfectly piecewise linear output $V_{\mathrm{OL}}(\theta)$

$$V_{OL}(\theta) = V_O(\theta) + C(\theta) \approx PT(\theta). \tag{7.9}$$

The compensation signal $C(\theta)$ is given by;

$$C(\theta) = PT(\theta) - V_O(\theta) \tag{7.10}$$

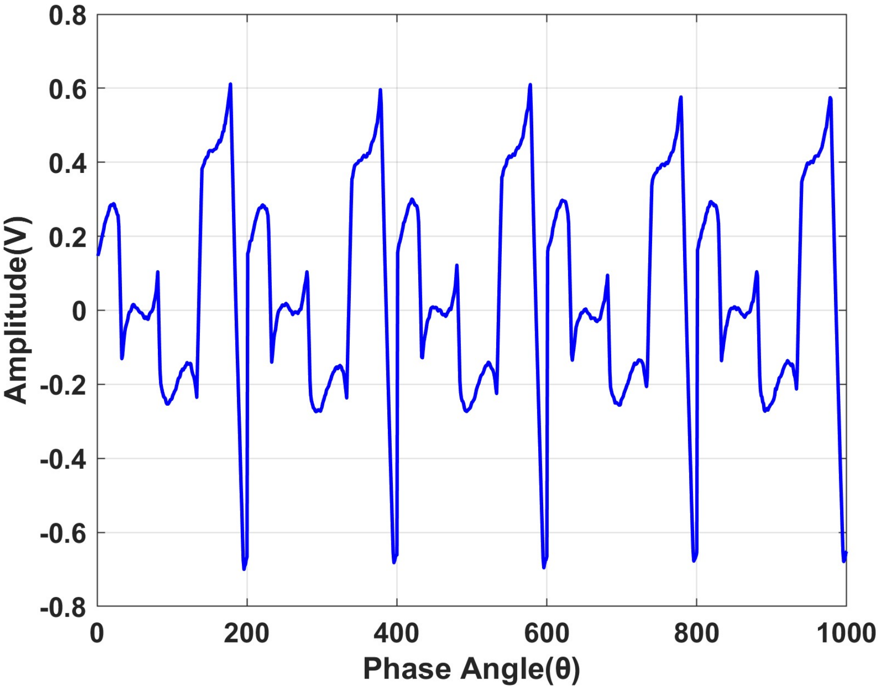


Figure 7.9: Error Signal.

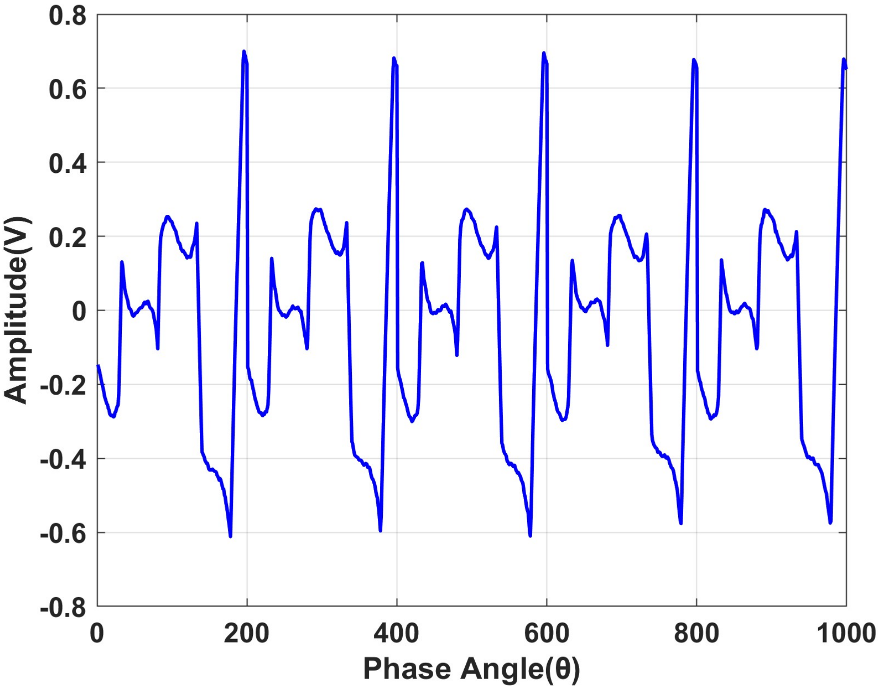


Figure 7.10: Compensation Signal.

From the compensation signals, it is evident that a single fitting process is insufficient to compensate for the errors. Therefore, two types of fitting processes are utilized for correction. The fitting process is performed segment by segment, with each segment taken from the compensation signal. After seven segments, the compensation signal is repeated. These seven segments are considered as one cycle, and the fitting process is used to correct this cycle. This approach is likely applicable to subsequent cycles as well.

When it comes to fitting the compensation signal, using both linear and cubic fitting methods offers several advantages.

- Linear Fitting:

    1. Simplicity: Linear fitting is straightforward and easy to understand. It involves fitting a straight line to the data, which allows for simple interpretation and explanation of the relationship between variables.
    2. Computational Efficiency: Linear fitting involves solving a system of linear equations, which is computationally efficient. This efficiency is especially useful when dealing with large datasets or real-time processing requirements.
    3. Interpret-ability: The coefficients obtained from linear fitting have direct interpretations. The slope coefficient represents the rate of change, while the intercept represents the starting point of the relationship between variables. This makes it easier to interpret the impact of the independent variables on the dependent variable.

- Cubic Fitting:

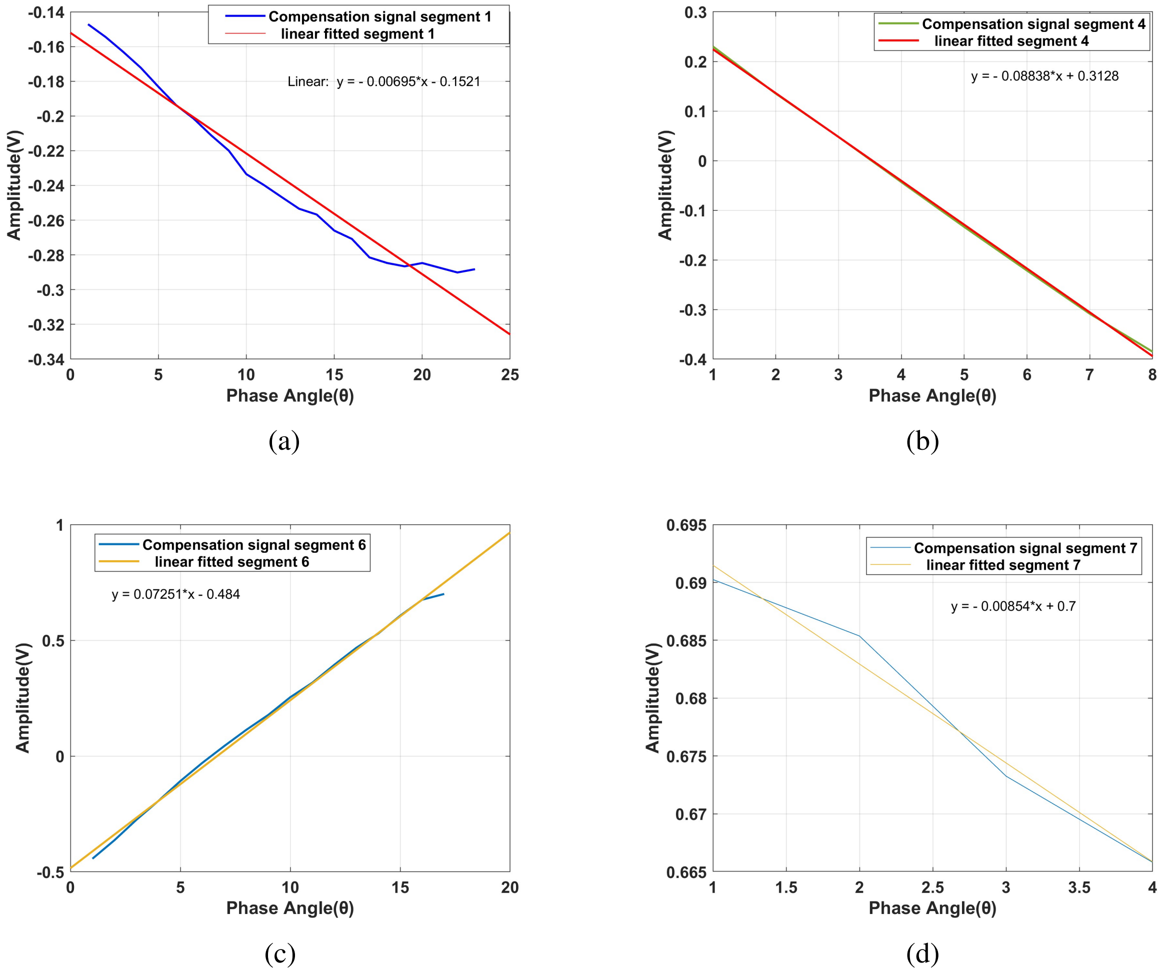
1. Flexibility in Representing Curvature: Cubic fitting can capture more complex and nonlinear relationships between variables compared to linear fitting. It accommodates concave and convex curves, allowing for a more flexible representation of the curvature in the data.

2. Localized Curve Fitting: Cubic fitting focuses on fitting curves within small local regions of the data. This localized approach enables better capturing of specific features and variations in the data within these regions. It can be especially effective when the compensation signal exhibits localized variations or complex patterns.

3. Reduced Sensitivity to Outliers: Cubic fitting tends to be less sensitive to outliers compared to linear fitting. By using higher-order polynomials, cubic fitting can minimize the influence of outliers and provide more robust results.

Using both linear and cubic fitting methods for the compensation signal allows for a comprehensive approach to error correction. Linear fitting can address overall trends and systematic errors, while cubic fitting can capture localized variations and complex patterns that may exist in the signal. This combination helps ensure that both the global and local aspects of the compensation signal are appropriately accounted for in the fitting process.

By leveraging the advantages of both linear and cubic fitting, it is possible to achieve more accurate and reliable compensation of errors in the signal, leading to improved performance and more precise measurements.



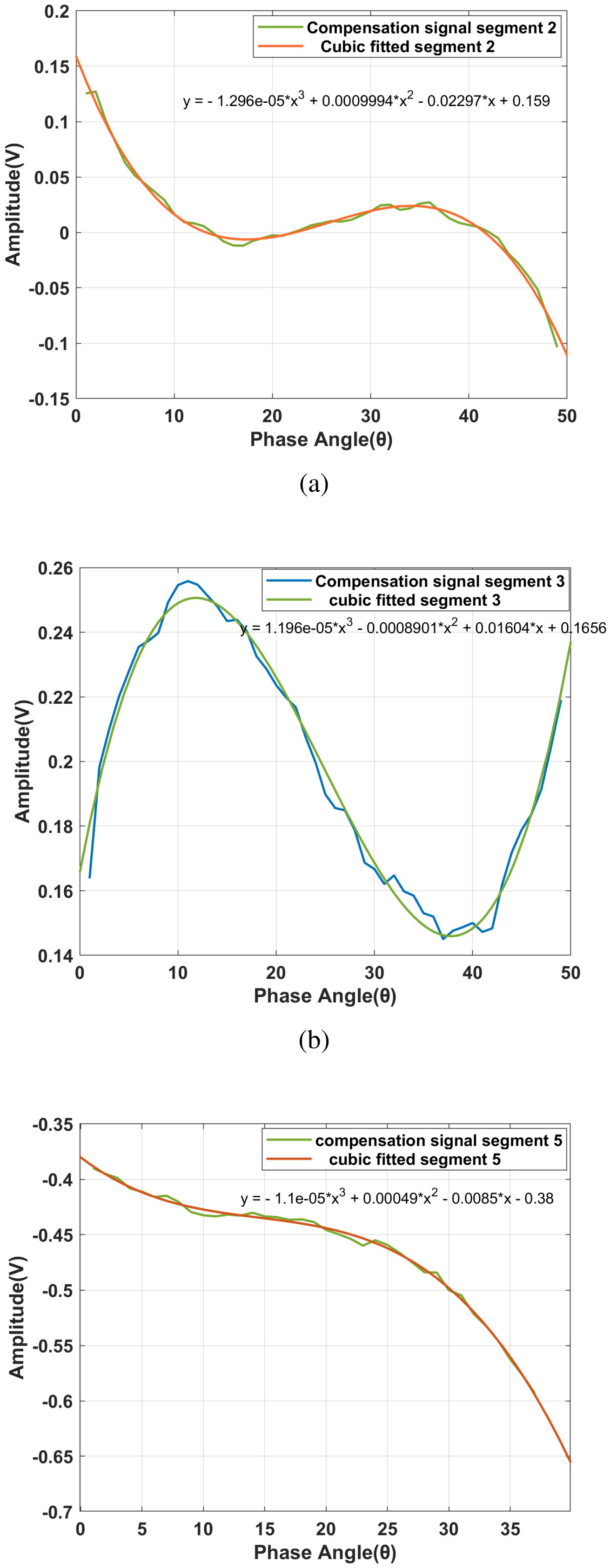
(a)

(b)

(c)

(d)

Figure 7.11: Compensation signal linear fitting (a) Segment 1; (b) Segment 4 ; (b) Segment 6 ; (b) Segment 7.



(a)

(b)

(c)

Figure 7.12: Compensation signal cubic fitting (a) Segment 2**;** (b) Segment 3 **;** (c) Segment 5

Table 7.2: Compensation signal fitting- Cycle 1

Segment	coefficient 1	coefficient 2	coefficient 3	coefficient 4	Norm Residual
1	-0.006949744	-0.15210033			0.048204421
2	-1.30E-05	0.000999381	-0.022973727	0.159005556	0.030119058
3	1.20E-05	-0.00089011	0.016041177	0.165623865	0.029760262
4	-0.088380375	0.312755645			0.012893681
5	-1.13E-05	0.00049053	-0.008487847	-0.380192081	0.017287553
6	0.072507938	-0.484018875			0.075806417
7	-0.00854011	0.70002492			0.002950725

For the correction process, linear fitting is employed for segments 1, 4, 6, and 7, is shown in Fig 7.11 while cubic fitting is used for segments 2, 3, and 5 is shown in Fig 7.12. The choice of fitting method for each segment is determined based on the characteristics and requirements of the specific segment.

Table 7.3: Compensation signal fitting- Cycle 2

Segment	coefficient 1	coefficient 2	coefficient 3	coefficient 4	Norm Residual
1	-0.006447558	-0.158836941			0.050274176
2	-1.38E-05	0.001050585	-0.024164476	0.162912717	0.023552256
3	1.18E-05	-0.000884919	0.015324023	0.198336213	0.038525168
4	-0.085234822	0.313743			0.015190474
5	-1.18E-05	0.000520583	-0.008606332	-0.36164426	0.025536008
6	0.073382981	-0.509659932			0.084894465
7	-0.007194374	0.68219506			0.001566825

The table provided presents the results of the fitting process for different segments in two cycles. In the first cycle, segments 1, 4, 6, and 7 utilize linear fitting, while segments 2, 3, and 5 employ cubic fitting. Similarly, in the second cycle, the same fitting methods are used for their respective segments.

Comparing the coefficients between the two tables, it is clear that the coefficients in each table are nearly equal. This suggests that the correction applied to the coefficients in one cycle automatically corrects the coefficients in subsequent cycles. Therefore, it can be concluded that by correcting the coefficients in a single cycle, the remaining cycles are automatically corrected without the need for additional adjustments.

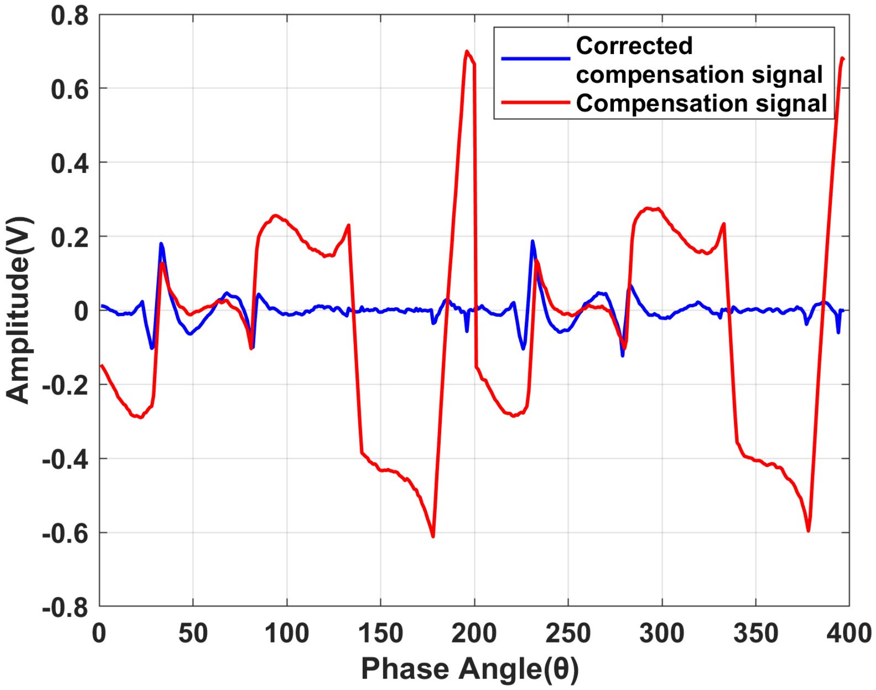


Figure 7.13: Compensation Signal after fitting process.

By applying the fitting method to the compensation signal, the errors are effectively reduced within the range of 0.2 to 0 V is showm in Fig 7.13.

The fitting process aims to find the best-fitting curve or line that closely matches the compensation signal data points. By adjusting the coefficients or parameters of the fitting model, the fitted curve is optimized to minimize the errors within the specified range. This reduction in error helps to improve the accuracy and reliability of the compensation signal.

By minimizing the error within the desired range, the fitting method ensures that the compensated signal aligns more closely with the true underlying values. This reduction in error allows for more precise measurements and enhances the overall quality of the signal analysis or system performance.

Overall, the application of the fitting method effectively minimizes the error within the range of 0.2 to 0 V, contributing to improved accuracy and reliability in the compensation signal.

7.7 SUMMARY

This chapter explores methods to reduce errors and improve accuracy in optical encoders. Normalization removes bias and improves consistency, while linear interpolation smooths irregularities and provides a more accurate representation of the encoder's position. Harmonic approximation decomposes repeating signals into constituent frequencies, minimizing errors and improving overall accuracy. The ratiometric technique enhances linearity in output signals by calculating the difference to the sum of two sinusoidal signals. These methods collectively contribute to reducing errors and improving the accuracy of optical encoders, making them more reliable and precise in various applications.

Chapter 8

CONCLUSION

8.1 CONCLUSION

This report provided an overview of optical encoders and the various errors associated with them. Optical encoders are devices used for position sensing and are available in different types based on their design and configuration. The errors in optical encoders were classified as wide angle and narrow angle errors, which can affect the accuracy of position measurements.

A specific focus is given to the analysis of a 19-bit encoder, which has a high resolution. The fine rollover and coarse correction methods are discussed as effective techniques for identifying the specific bits where errors occur. Analysis methods such as phase difference, amplitude difference, and spectral errors were utilized to determine the nature and extent of the errors.

Furthermore, the report explored the Nonious encoder, which is a type of lower bit encoder. The configuration and operation of the Nonious encoder were explained, along with various compensation techniques to improve its accuracy. The methods of linear interpolation, harmonic approximation, and ratio metric technique were introduced as effective means of reducing errors and enhancing the performance of the Nonious encoder.

Applying these compensation techniques, the errors in optical encoders can be mitigated, leading to improved accuracy and overall performance. These techniques play a crucial role in achieving precise and reliable position sensing in various applications. Continued research and development in error analysis and compensation methods will further enhance the accuracy and effectiveness of optical encoders in the future.

Table 8.1: Compensation Techniques for Optical Encoders

Sl No.	**Compensation Technique**	**Outcome**
1	Bias Normalization	Bias normalization enhances optical encoders' output sine/cosine signals by eliminating systematic errors.
2	Arc-Tan Method	It determines an angle value by measuring the phase difference between sine and cosine signals. It uses a process for calculating the rotation's position or angle.
3	Complementary Method	Second harmonic cancellation reduces errors in signals by creating an anti-phase signal aligned with the original signal's second harmonic components, but may not achieve desired reduction.
4	Linear Interpolation	Linear interpolation estimates absolute angles between known angles and positions, with accuracy based on data points' linearity and distribution. It is useful for estimating intermediate values, but residual values can introduce errors in the -6 to +6 V range.
5	Harmonic Approximation	The technique reduces the residual waveform range to 0.2 to 0 V, reducing computational complexity and data size, resulting in a more concise representation with a smaller range of values.
6	Ratio Metric Technique	Improve encoder readings by reducing errors in sine and cosine signals using ratio values and techniques like phase difference and spectral analysis. Fitting method minimizes errors within 0.2 to 0 V, ensuring accurate measurements and enhanced system performance.

8.2 FUTURE SCOPE

In the future, there are several potential areas of exploration and development in the field of optical encoders and error compensation techniques. Some of the possible future directions include:

1. Advanced Error Analysis: Further research can be conducted to delve deeper into the analysis of errors in optical encoders. This may involve investigating more sophisticated mathematical models and algorithms to accurately identify and quantify different types of errors, including non-linear errors and complex error patterns.

2. Enhanced Compensation Techniques: The existing compensation techniques, such as linear interpolation, harmonic approximation, and ratio metric technique, can be further refined and optimized. New algorithms and approaches can be developed to improve the compensation accuracy, reduce residual errors, and enhance the overall performance of optical encoders.

3. Integration of Machine Learning and Artificial Intelligence: Machine learning and artificial intelligence techniques can be applied to error analysis and compensation in optical encoders. These advanced technologies can learn from the encoder's performance data and adaptively adjust compensation parameters to optimize accuracy. This may lead to real-time error correction and improved stability in dynamic operating conditions.

4. Development of Multi-Sensor Fusion Techniques: Integration of optical encoders with other types of sensors, such as inertial sensors or magnetic sensors, can enable multi-sensor fusion techniques. By combining data from multiple sensors, it becomes possible to achieve higher accuracy, redundancy, and fault tolerance in position sensing applications.

5. Miniaturization and Integration: Continued advancements in miniaturization and integration technologies can lead to the development of smaller, more compact, and highly integrated optical encoders. This can facilitate their integration into space-constrained applications, such as robotics, medical devices, and consumer electronics.

6. Application-Specific Optimization: Future research can focus on tailoring error analysis and compensation techniques for specific application domains. Different applications

may have unique error characteristics and requirements, and customized compensation methods can be developed to achieve the best possible accuracy and performance in those specific applications.

Overall, the future scope of optical encoders lies in the continuous refinement of error analysis and compensation techniques, integration with advanced technologies, and the development of application-specific solutions. These advancements will contribute to the ongoing improvement of accuracy, reliability, and usability of optical encoders in various industries and applications.

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