CT310 APPLICATION GUIDE

By Allegro MicroSystems

INTRODUCTION

Numerous applications in automotive, industrial, and consumer markets require monitoring of a rotating mechanical structure. The position sensing of the angle, speed, and direction of motor shafts and knobs are typical applications for angle sensors.

This application note refers to the CT310 angle sensor product from Allegro and provides guidelines and recommendations to implement the CT310 in angle-sensing or rotation applications.

The two fundamental components of any angle-measurement system are the magnet, including its placement relative to the sensor, and the angle sensor, including its intrinsic performance. Both components are reviewed in this application note.

CT310 INTRODUCTION

The CT310 refers to the family of angle sensor products offered by Allegro. Based on Allegro-proprietary tunnel magnetoresistance (TMR) technology (MLUTM), the CT310 offers inherent advantages compared to other angle-sensing technologies.

TMR Effect

The CT310 makes use of the TMR effect that manifests in a change of electrical resistance of a stack of materials (including ferromagnetic alloys). To learn more about TMR technology and its properties, refer to From Hall Effect to TMR (Allegro application note AN117).

The TMR effect is a natural angle sensor. The resistance of the TMR stack correlates directly with the angle between the sense layer and the fixed layer. This allows the CT310 many advantages compared to other technologies:

- Full 360° rotation discrimination.
- Sensitivity to only the angle, not the strength of the external field.

The CT310 borrows similar advantages of contactless systems:

- Free of mechanical wear and tear.
- Safe from dust and contamination.
- Independent of mechanical vibration.

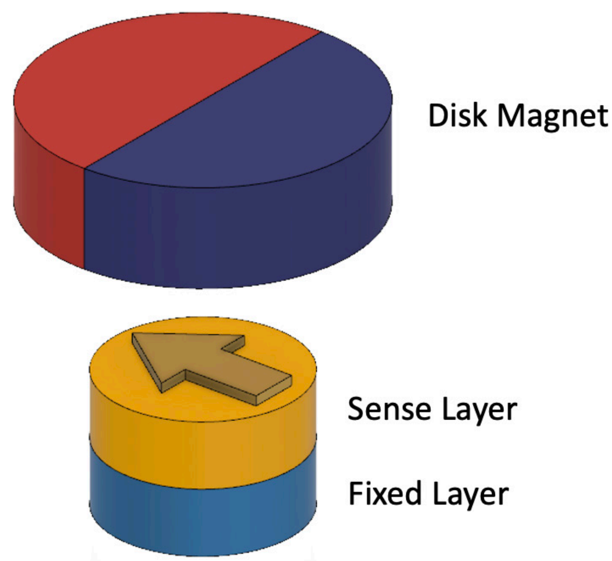

Figure 1: Typical TMR Junction Including Sense Layer, Fixed (or Reference) Layer, and External Magnet Applying Magnetic Field to Sense Layer

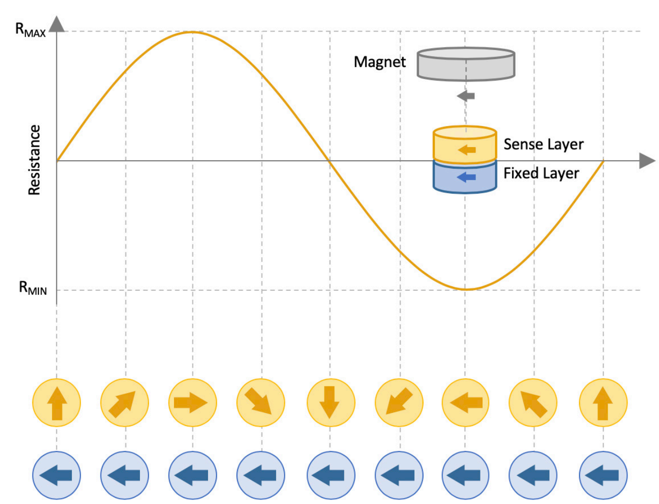

Figure 2: Normalized Resistance Output of TMR Junction Under Rotating External Magnetic Field

Bridge Configuration

The CT310 features two Wheatstone bridges for X and Y component detection. Both bridges are on the same die making the CT310 a monolithic sensor, which improves all the parameters of the sensor, including:

- Angle error.
- Amplitude matching (synchronism).
- Temperature stability.

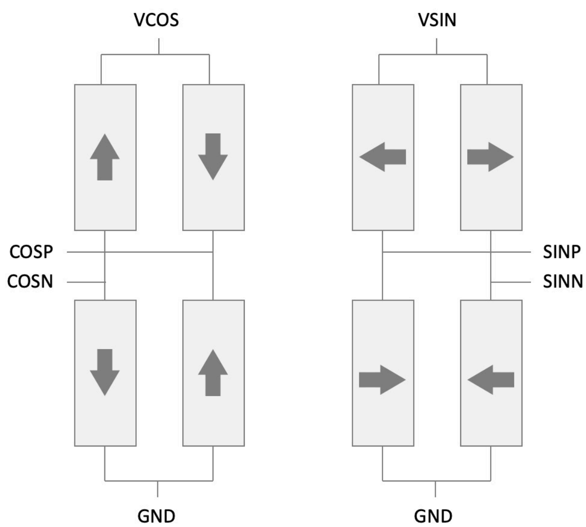

Figure 3: Typical Angle Sensor Including Two Wheatstone Bridges

The CT310 makes full use of the magnetic-logic-unit (MLU) technology to magnetically merge the cosine (COS) and sine (SIN) sensing elements. Thus, the CT310 pushes closer to the perfect "dot" sensor, where the COS and SIN sensing elements observe the exact same external magnetic vector, as further described in the application note.

Package Types

Allegro offers the CT310 in two industry-standard packages: an 8-lead TSSOP and a very-low-profile, small-form-factor 8-lead, 2 mm × 2 mm × 0.45 mm DFN package. The small DFN package allows for difficult sensor-to-magnet arrangements, especially in the case of linear and off-shaft placements.

For a complete description and specifications of the available packages, refer to the CT310 datasheet.

MECHANICAL DESCRIPTION

On-Shaft

The on-shaft (or end-of-shaft) arrangement is the most common configuration. A diametral magnet is mounted on the rotating shaft, and the sensor is placed underneath the magnet. The vertical spacing between the magnet and top of the sensor package is referred to as the air gap.

The CT310 is ideally placed on the center of the rotating magnet to ensure that, during a full 360° rotation, the sensor observes a uniform field. An example of the CT310 with the magnet mounted in an on-shaft position is shown in Figure 4.

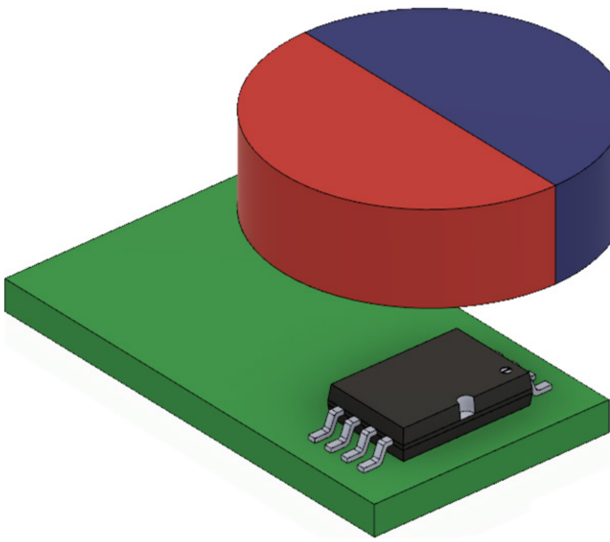

Figure 4: CT310 in TSSOP-8 Package with Disk Magnet Mounted in On-Shaft Position

Off-Shaft

The off-shaft (or side-shaft) arrangement is preferred in some applications where the on-shaft arrangement is mechanically difficult to implement.

The CT310 is placed outside and adjacent to the ring or disk magnet. Or, in some applications, the CT310 is placed inside the ring magnet.

In this configuration, shown in Figure 5 using a disk magnet, a two-pole magnet, the magnetic field is not uniform when performing a full 360° rotation. Hence, the output of the CT310 reflects this nonuniformity.

The nonuniformity of the magnetic field as it impacts the Angle error is shown in Figure 7. Linearization methods can be applied to compensate for this effect.

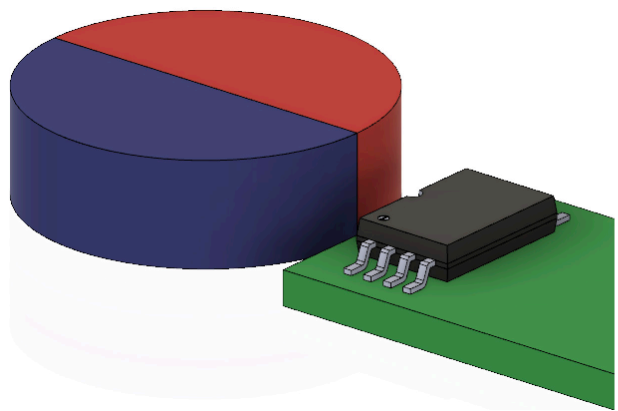

Figure 5: Off-Shaft Mounting of CT310

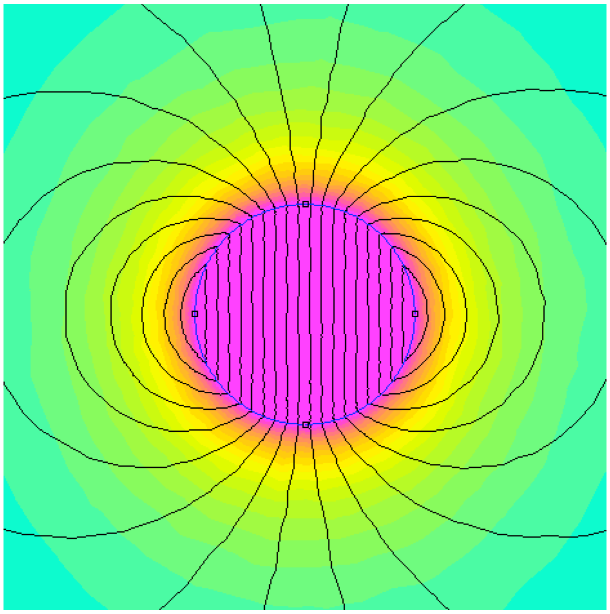

Figure 6: Magnetic Field Generated By Disk Magnet

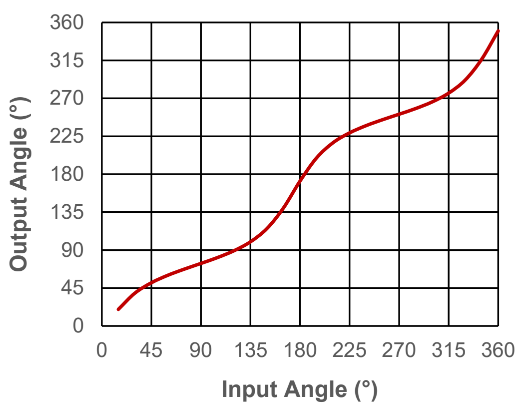

Figure 7: Off-Shaft Nonlinearity

Linear Sensing

The CT310 can be used for temperature-independent linear position sensing.

Typically, for a linear position application, a linear magnetic sensor can be used (refer to the Allegro CT100). However, as explained in this application note, all magnets have a temperature coefficient. This means that the magnetic field strength of the magnet changes due to temperature variation, which leads to reading errors. Because the linear sensor cannot distinguish between a real change of position of the distance or a change in the magnetic field due to temperature, one solution is to make use of magnets with low temperature coefficients, which are typically more onerous and costlier.

The CT310 can be used in these harsh environments because the angle reading is independent from the temperature coefficient of the magnet as long as the magnetic-field strength is above the minimum required operating-field strength of 20 mT (200 G).

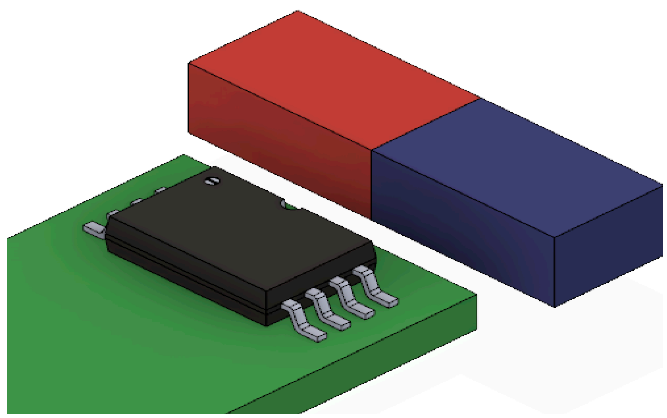

Figure 8: CT310 and Bar Magnet Mounting for Linear Movement Detection

MAGNET CONFIGURATION

Introduction

Magnets come in different shapes, sizes, and materials. This application note does not provide a detailed analysis of the performance of the CT310 using different magnets. However, this application note provides a general overview and basic recommendations to allow a design engineer to start using the CT310 with their magnets.

Magnet Material

Readily available magnets typically fit into two categories: rare earth magnets and ferrite magnets. Rare earth magnets are known for their high-remanence (B_r) fields, while ferrite magnets are lower cost.

Remanences affect the measured strength of the magnetic field generated by the magnet. Stronger fields usually allow for relaxed mechanical tolerances of air gap and alignment.

The temperature coefficient of the material remanence is also important to consider, especially in extreme temperature environments (i.e., –40°C or 150°C). Typically, magnetic materials have negative temperature coefficients, which means the magnetic-field strength decreases as the temperature increases. Primary types of magnet materials are compared in Table 1.

NOTE: Values listed in Table 1are for reference. Both the Br and temperature coefficient can be tweaked by magnet manufacturers. For exact magnet specifications and proprieties, refer to the datasheet from the magnet manufacturer.

Bonded magnets are typically formed by injection-molding techniques that allow fabrication of different shapes and sizes of magnets. The material used for the magnet maintains the same temperature coefficient properties; however, the remanence (or magnetic strength) is typically reduced.

Table 1: Overview of Parameters of Widely Available Magnetic Materials

Material	Material Name	B_r	Temperature Coefficient
NdFeB	Neodymium	1300	–0.10%/K
SmCo	Samarium-Cobalt	1000	–0.04%/K
AlNiCo	Aluminum Nickel Cobalt	900	–0.02%/K
	Bonded NdFeB	450	–0.10%/K

Magnet Shape

The shape of the magnet does not impact the performance of the CT310: As long as the rotation is less than the full 360°, the magnet generates a homogenous field.

Typically, for 2D applications, disk or ring magnets with diametral magnetization are used. An off-shaft mounting of a six-pole ring magnet is shown in Figure 9. These magnets are typically used in encoders to increase the resolution of the system.

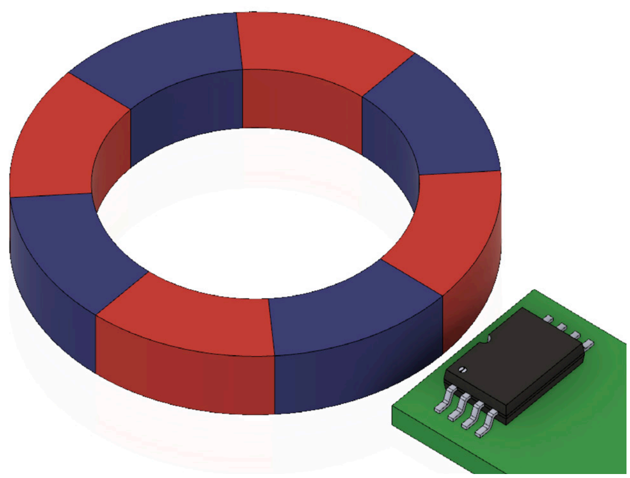

Figure 9: Representation of Side-Shaft Mounting of a Six-Pole Ring Magnet

Eccentricity and Air Gap

The total accuracy of any angle-measurement system depends on the accuracy of its three elements:

- Mechanical centering of the axis of rotation, magnet, and sensor positions.
- Material and build quality of the magnet.
- Intrinsic linearity error of the angle sensor.

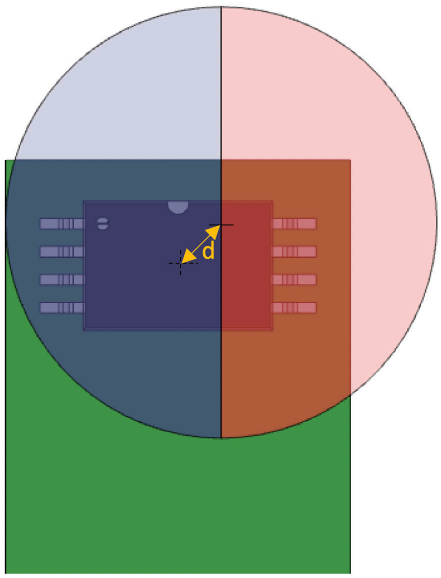

Figure 10: Top View of CT310 and On-Shaft-Mounted Magnet Showing Misalignment By Distance (d)

Eccentricity refers to an in-plane (X, Y) misalignment. This is usually due to the off-centered rotating shaft. The eccentricity effect on accuracy can be reduced using large-diameter magnets.

The change in Angle error when the magnet is misaligned is shown in Figure 11. The magnet used for this test is a standard N42 NdFeB, 20 mm in diameter and 9.5 mm in thickness.

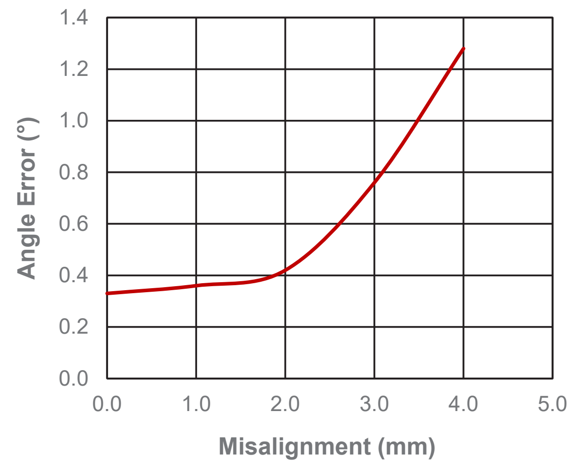

Figure 11: Evolution of CT310 Calculated Angle Error When Magnet Is Misaligned By Different Distances

The air gap refers to the vertical spacing between the magnet and sensor. The air gap is directly related to the magnetic-field strength and needs to be adjusted to apply a magnetic field within the operating range of the CT310. The relationship between the magnetic-field strength and air gap is shown in Figure 12. The magnet used for this analysis is a standard N42 NdFeB, 20 mm in diameter and 9.5 mm in thickness.

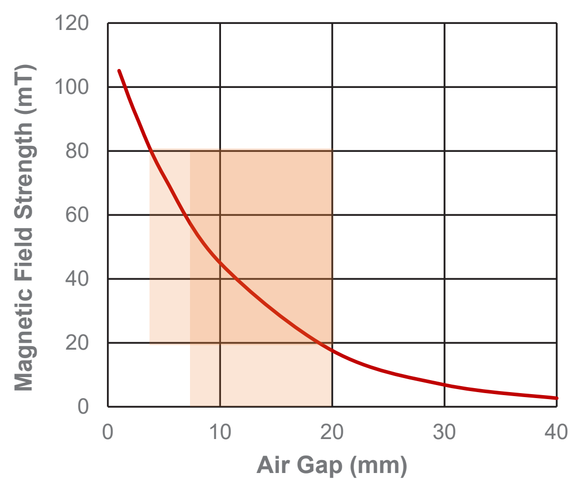

Figure 12: Typical Magnetic Field Strength Decay vs. Distance (Air Gap)

SENSOR PERFORMANCE

The CT310 sensor achieves excellent Angle accuracy. Moreover, the inherent benefits of Allegro-proprietary TMR enable an easier implementation of the CT310.

A review of the main performance metrics needed by designers to implement the CT310 sensor follows.

Close to a "Dot" Sensor

Ideally, all the magnetic sensing elements of an angle sensor are exposed to the same external magnetic field. In practice, this is hard to achieve due to the nature of the magnetic field generated by a single magnet. Hence, two parameters in the design of an angle sensor are crucial to mitigating this effect.

Size of Sensor

The total area covered by an angle sensor is critical to minimize the effect of a change of measured external field. The bigger the area covered by the sensor, the bigger the magnet required.

The CT310 total sensitive area is 300 µm × 300 µm. The small size allows for the use of very-small-diameter magnets and improves the accuracy of the angle-measuring system.

Location of X and Y Sensing Elements

Typically, the X and Y sensing elements are physically separated and processed within silicon to be 90° apart. Of course, using multiple dice inside a package to achieve an angle sensor inherently yields inferior performance. The CT310, however, consists of two Wheatstone bridges, each consisting of four TMR elements where each TMR element comprises multiple TMR junctions. Allegro-proprietary TMR processing and fixed-layer programming allows for the physical mixing of the X and Y sensing Wheatstone bridges. Only the reference layer of the TMR junction gives it the ability to sense the X or Y component of the external magnetic field. This enables the CT310 to physically mix the X and Y sensing elements to further improve the performance.

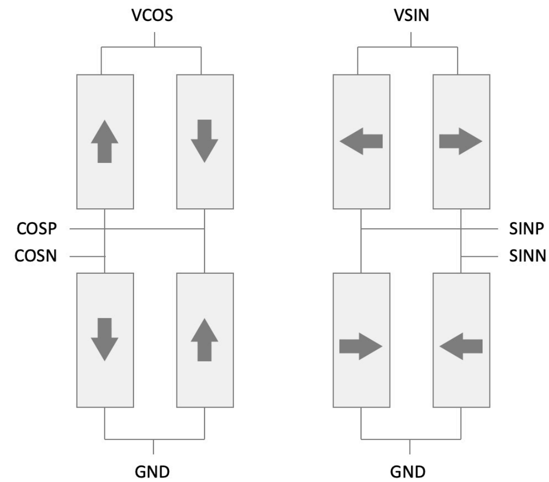

Figure 13: Typical Angle Sensor Including Two Wheatstone Bridges

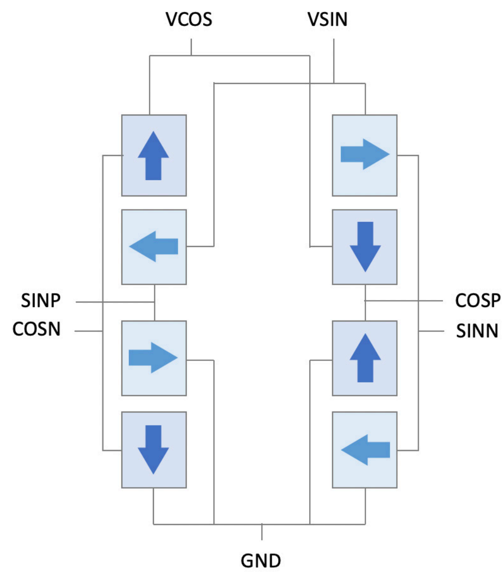

Figure 14: Closer Representation of Actual CT310 Magnetic Configuration

Not a Linear Sensor

The goal of an angle-sensor sensing element is to provide a voltage output that reflects the angle of the external field. This voltage output should not change due to a change in the magnetic field strength. Otherwise, careful amplitude matching, and temperature compensation needs to be executed before the angle decoding stage. This is the case for Hall-effect-based angle sensors, which adds latency.

The operating range of the CT310 is 20 mT to 80 mT. This range guarantees that the CT310 TMR junctions are in saturation. Increasing the magnetic field strength does not yield a different voltage output; however, rotating the external field 180° saturates the TMR junctions in the opposite magnetization. This means that only the angle of the external field allows a change in the voltage output.

More about the behavior of the TMR junctions used in the CT310 can be found in Allegro application note TMR for 2D Angle Sensing (AN119).

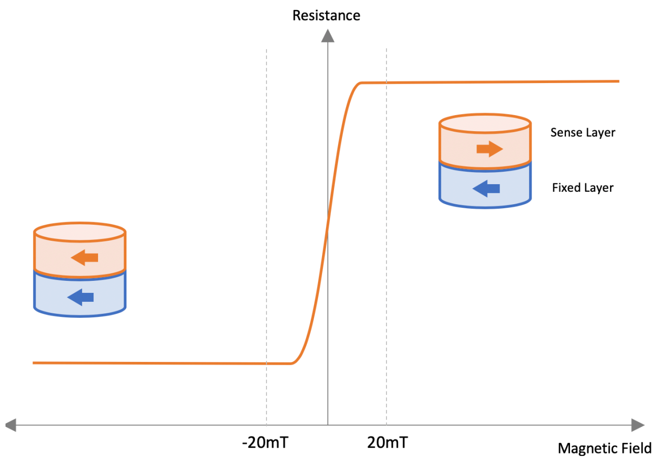

Figure 15: Shows Linear and Saturation Regions of Typical TMR Junction

Amplitude Synchronism

Amplitude matching (or amplitude synchronism) describes how identical the SINE and COSINE outputs are relative to each other. Ideally, this number should be 100% under the entire operating range (including field and temperature).

As described before, this is easier to achieve using TMR, which allows for better performance and easier implementation.

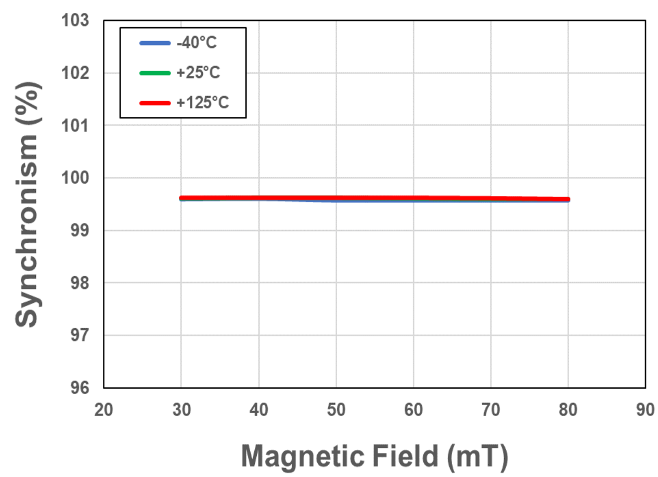

Figure 16: Amplitude Matching Over Different Fields and Temperatures

Single Die

Many of the previously stated parameters can only be achieved using a monolithic solution. Temperature behavior, synchronism, offset, and total size of the sensor are positively impacted by the monolithic design of the CT310.

Temperature

The change of the CT310 parameters over temperature was of major importance during the development of the CT310. This section is a general overview of the change of different parameters over temperature.

Angle Error

Angle error is defined by the difference between the position of the magnet and the calculated output from the CT310.

The amplitude of the deviation from a perfect straight line between 0° and 360° is calculated as:

$$Angle\ Error = (E_{MAX} - E_{MIN})/2$$

The angle error shown only includes offset subtraction and amplitude normalization.

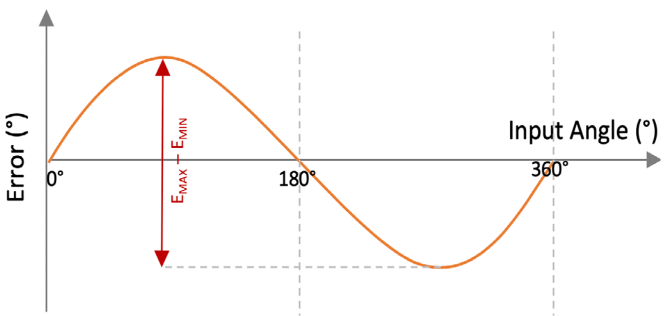

Figure 17: Angle Error Representation

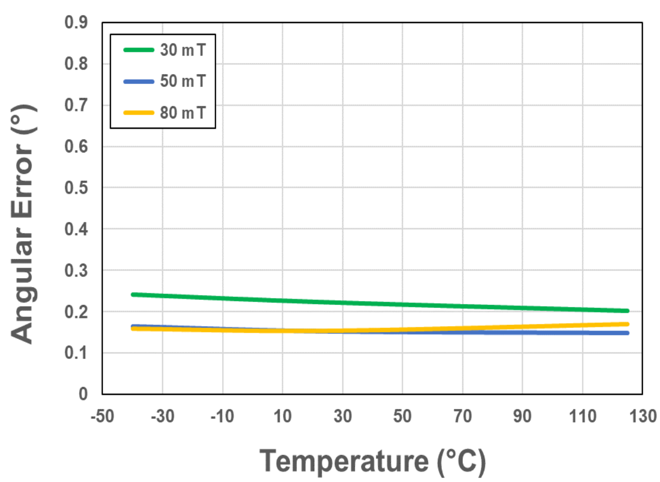

Figure 18: Angle Error over Different Fields and Temperatures

Synchronism

Synchronism (i.e., amplitude matching) is crucial for operation and ease of implementation of an angle sensor.

Matching of the X and Y bridges for an angle sensor is critical because the angle is effectively the ratio of both output (as described next).

When the technologies do not provide perfectly matched X and Y bridges, further circuitry and tedious calibration are needed to adjust and match the amplitude before the angle-decoding stage.

The Allegro TMR technology and the monolithic nature of the CT310 allow near-ideal matching under different magnetic-field strengths and over a wide temperature range, thus removing the need for extensive matching circuitry and calibration.

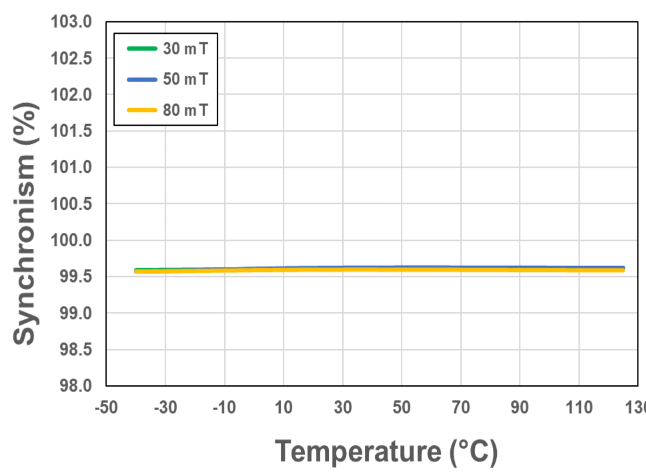

Figure 19: Synchronism over Different Fields and Temperatures

Offset

Offset is also a major contributor to angle error. Simply calibrating for offset (i.e., subtracting the X and Y offsets) results in overall angle error of less than 1°.

The stable performance of offset over a wide temperature range is shown in Figure 20. This allows for an easier compensation procedure by simple subtraction of the same fixed offset voltage.

Orthogonality

Orthogonality refers to the phase shift measured between the X and Y outputs under a full rotation. Ideally, the phase shift should be 90°.

The near-ideal performance of the CT310, where orthogonality is not affected by the external magnetic field, is shown in Figure 21.

The raw orthogonality of the CT310 is such that the system designer avoids the heavy cost of orthogonality correction. However, for applications that require angle error of less than 0.3°, orthogonality correction is recommended.

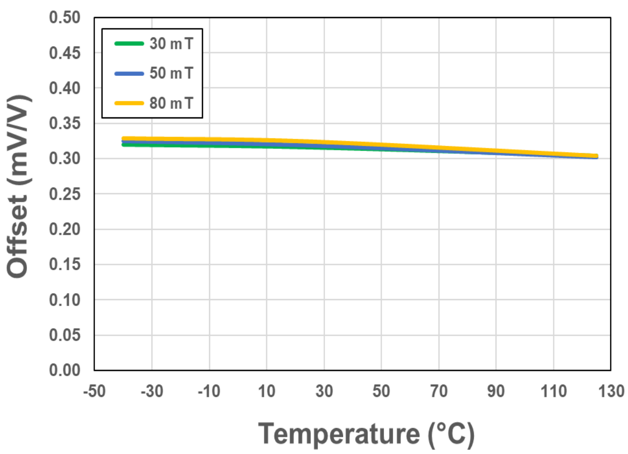

Figure 20: Offset Over Different Fields and Temperatures

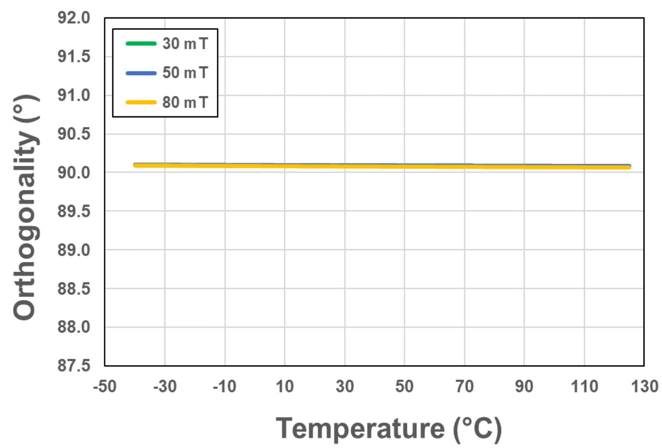

Figure 21: Orthogonality Over Different Fields and Temperatures

CALIBRATION PROCEDURE

No Calibration

The CT310 can be used without any calibration for applications where the absolute angle error is not application critical.

The graphs shown previously demonstrate the performance of the CT310 including amplitude matching (i.e., synchronism), offset and orthogonality over different fields and different temperatures. The block diagram in Figure 22 shows how the CT310 can be connected to a microcontroller unit (MCU), including analog-to-digital converters (ADCs). The CORDIC algorithm, involving the calculation of the arctan function, is used to determine the angle. This angle-decoding procedure is described in the Angle-Decoding Procedure section.

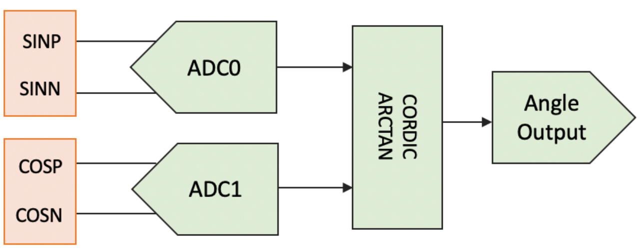

Figure 22: Typical Block Diagram of Voltage-Sampling and Angle Calculation

Calibration Procedure

Once the mechanical setup is completed, the offset and amplitude of the output signals can be sampled over one full 360° rotation.

The needed offset and amplitude corrections can be determined by simply saving the maximum (MAX) and minimum (MIN) values of both X and Y.

This application note details only the offset and amplitude correction. These corrections require simple arithmetic operations by the MCU.

Offset Correction

The offset of each bridge can be measured using:

$$V_{Xoffset} = (V_{XMAX} + V_{XMIN})/2$$
$$V_{Yoffset} = (V_{YMAX} + V_{YMIN})/2$$

Both offset voltages are calculated once after the initial full 360° rotation, then are stored for the entire operating lifetime of the CT310.

Simply subtracting the offset calculated value from the continuous measurements from the ADC removes errors due to offset.

Amplitude Correction

The goal of amplitude correction is to correct for the small mismatch of amplitude between the X and Y bridges of the CT310 by normalizing both output voltages to a value between –1 V and +1 V.

The amplitude of each bridge can be measured using:

$$V_{Xamplitude} = (V_{XMAX} - V_{XMIN})/2$$
$$V_{Yamplitude} = (V_{YMAX} - V_{YMIN})/2$$

Both amplitude voltages are also calculated once after the initial full 360° calibration rotation, then are stored for the entire operating lifetime of the CT310.

The normalized values can be calculated using:

$$V_{Xnorm} = V_X/V_{Xamplitude}$$
$$V_{Ynorm} = V_Y/V_{Yamplitude}$$

where V_X and V_Y are the ADC outputs.

Phase Error

When the outputs of the X and Y Wheatstone bridges are not exactly 90° out of phase with each other, this is considered to be a phase error.

The CT310 has negligible phase error due to the single-die concept and the TMR performance achieved.

Phase error can appear after sampling (i.e., after analog-to-digital conversion) if the X and Y bridges are not sampled simultaneously. It is recommended to use two independent ADCs to simultaneously measure the X and Y outputs of the CT310. Some ADCs offer a sample-and-hold feature that can also reduce the phase error. However, if only a single ADC is available on the MCU, it must convert sequentially X then Y. This error is greater with higher-speed systems (e.g., high-RPM motors).

ANGLE-DECODING PROCEDURE

The CT310 provides two differential analog outputs. Both V_X and V_Y voltages need to be sampled to extract the angle.

Referring to the CT310 datasheet:

$$V_X = V_{COSP} - V_{COSN}$$
$$V_Y = V_{SINP} - V_{SINN}$$

Differential-Input ADCs

The peak-to-peak voltage output of the CT310 is 0.35 V/V or 1.16 VPP using a 3.3 V supply voltage. This allows the CT310 to be directly connected to an ADC without the need for an amplification stage.

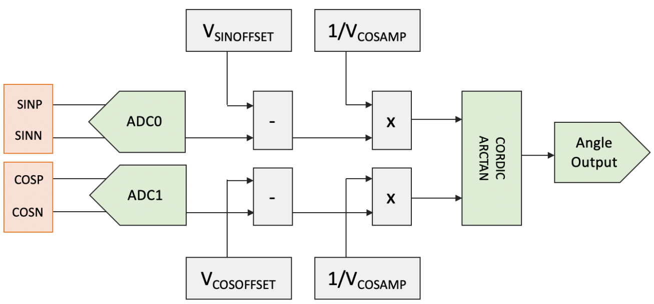

Figure 23: Typical Block Diagram of Voltage-Sampling and Angle Calculation with Offset Compensation and Amplitude Normalization

Single-Ended ADC Inputs

To convert the differential outputs of the CT310 to a single-ended output, the following circuit can be implemented using instrumentation amplifiers. The gain can be adjusted if needed. More importantly, the voltage becomes set at a new mid-voltage level around which the voltage output swings, which effectively level-shifts (i.e., offsets) the output of the CT310 which is described below.

$$V_{XOUT} = V_{REF} \pm V_{Xamplitude}$$
$$V_{YOUT} = V_{REF} \pm V_{Yamplitude}$$

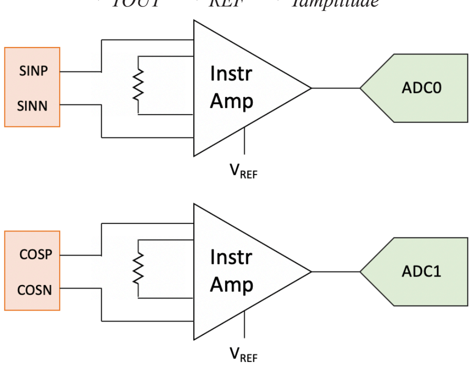

Figure 24: Typical Circuit to Adjust Gain and Offset of the CT310 Before the ADC Stage

Calculating the Angle

Once both V_X and V_Y voltages are converted and corrected for very low angle error, the angles can be extracted by solving:

$$\theta = arctan \times 2(V_Y/V_X) \times 180/\pi$$

This equation calculates the angle output in a range between –180° and 180°.

TERMS AND DEFINITIONS

The terms used in this document are defined below:

- Remanence (B_r): The strength of magnetization associated with a magnetic material. For two similarly shaped materials, higher remanence (B_r) yields stronger magnetic-field strength.
- Magnetic field: Refers to the vector field that describes the magnetic influence (or force) of an electric charge in relative motion or magnetized materials.
- Magnetic-field strength: Measured in A/m in the SI system. Refers to the magnitude and direction of a vector of the magnetic field.
- Magnetic-flux density: Measured in tesla in the SI system. It refers to the number of field lines and their direction passing through a certain area.

Revision History

Number	Date	Description	Responsibility
1	November 15, 2023	Document rebrand and minor editorial corrections	J. Henry