CT300 Application Guide

1 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 CT300 angle sensor product from Crocus Technology. It provides guidelines and recommendations to implement the CT300 in angle sensing or rotation applications.

The two fundamental components of any angle measurement system are the magnet, including its relative placement to the sensor, and the angle sensor, including its intrinsic performance.

Both components will be reviewed in this application note.

2 CT300 INTRODUCTION

The CT300 refers to the family of angle sensor products offered by Crocus Technology. Based on Crocus Technology's proprietary TMR technology (MLU^{TM}), the CT300 offers inherent advantages compared to other angle sensing technologies.

2.1 TMR EFFECT

The CT300 makes use of the Tunnel Magneto-Resistance (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, please refer to AN117.

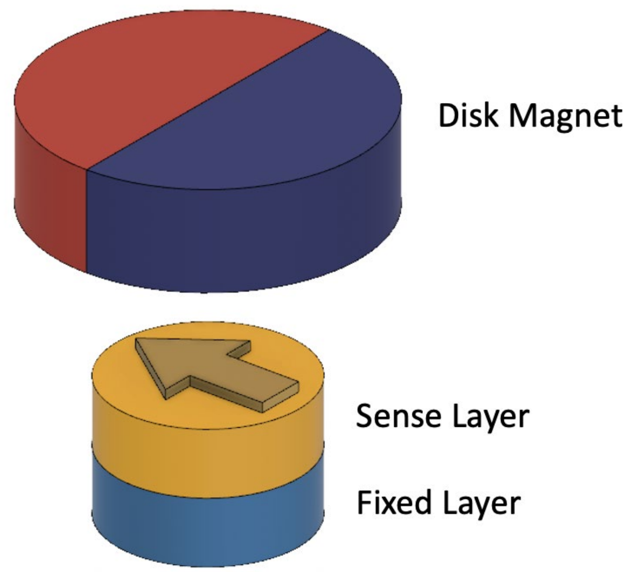

Figure 1. Representation of a typical TMR junction including a sense layer, fixed or reference layer and an external magnet applying a magnetic field to the sense layer.

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 CT300 many advantages compared to other technologies.

- Full 360° rotation discrimination
- Only sensitive to the angle and not the strength of the external field.

The CT300 borrows similar advantages of contactless systems:

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

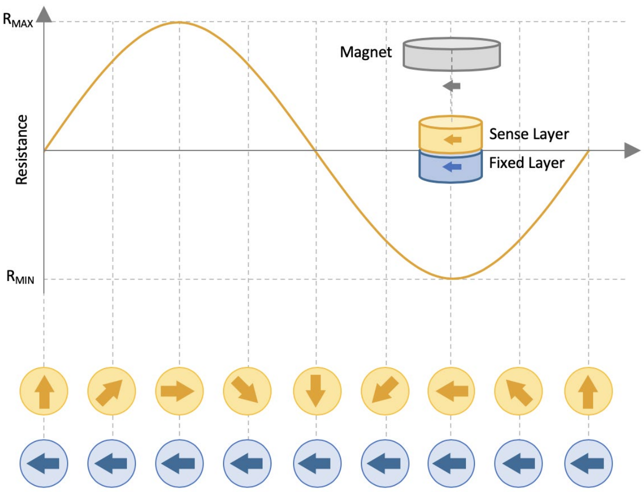

Figure 2. Shows the normalized resistance output of a TMR junction under rotating external magnetic field.

2.2 Bridge Configuration

The CT300 features two Wheatstone bridges for X and Y component detection. Both bridges are on the same die making the CT300 a monolithic sensor which improves all the parameters of the sensor, including:

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

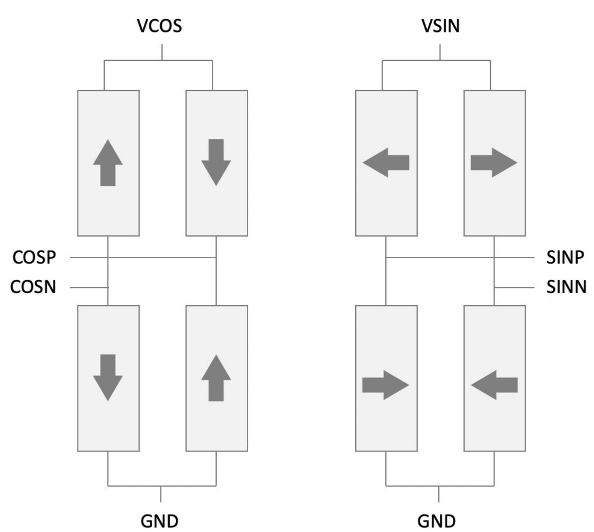

Figure 3. Typical representation of an angle sensor including two Wheatstone bridges.

The CT300 makes full use of the MLU technology to magnetically merge the Cosine (COS) and Sine (SIN) sensing elements. Thus, pushing the CT300 closer to the perfect "dot" sensor where the COS and SIN sensing elements see the exact same external magnetic vector. This will be further described below in the application note.

2.3 Package Types

Crocus Technology offers the CT300 in two industry standard packages: an 8-lead TSSOP and a very low profile, small form factor 8-lead, 2.00 × 2.00 × 0.45 mm DFN package.

Please refer to the CT300 datasheet for complete description and specifications of the available packages.

The small 2.00 × 2.00 × 0.45 mm DFN package allows for difficult sensor to magnet arrangements, especially in the case of linear and off-shaft placements.

3 MECHANICAL DESCRIPTION

3.1 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 "air gap".

The CT300 is ideally placed on the center of the rotating magnet to ensure that during a full 360° rotation the sensor sees a uniform field. Figure 4 shows an example of the CT300 with the magnet mounted in an on-shaft position.

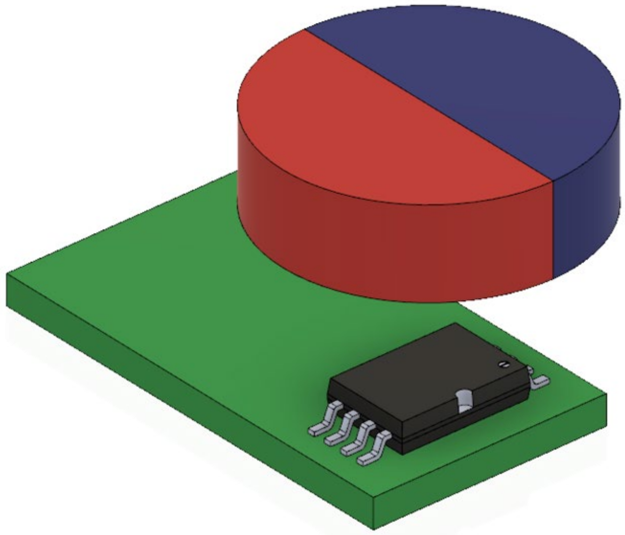

Figure 4. Shows a CT300 in TSSOP-8 package with a disk magnet mounted in an "on-shaft" position.

3.2 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 CT300 is placed outside and adjacent to the ring or disk magnet. Or, in some applications, the CT300 is placed inside the ring magnet.

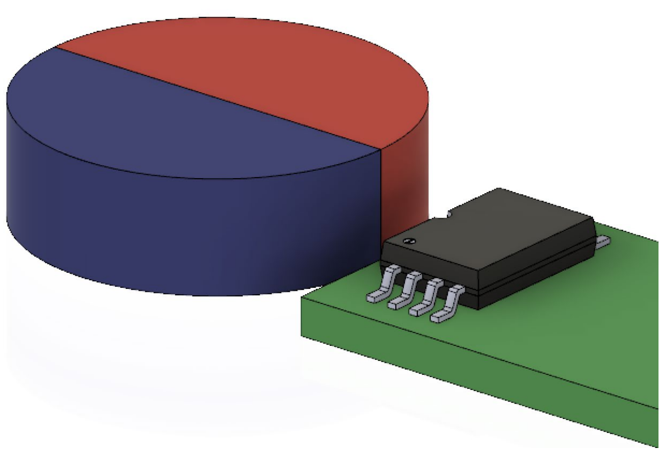

Figure 5. Represents an "off-shaft" mounting of the CT300.

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 CT300 will reflect this non-uniformity.

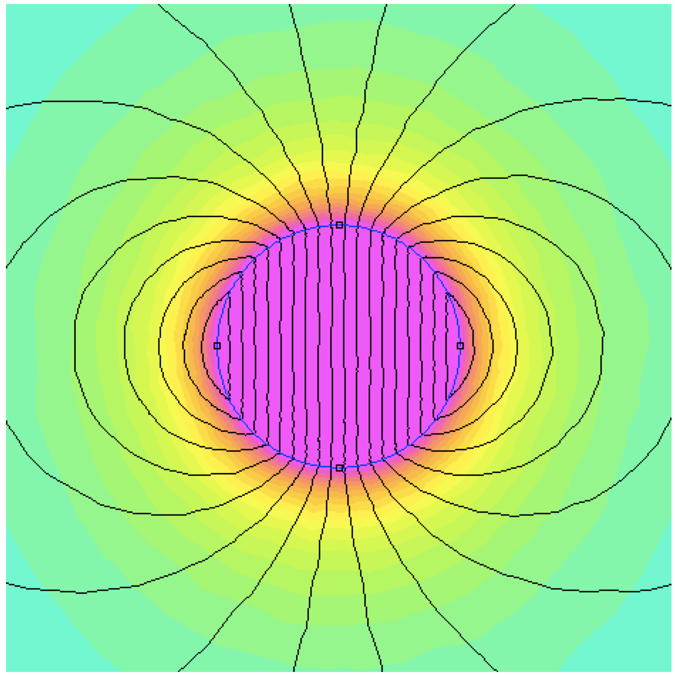

Figure 6. Magnetic field generated by a disk magnet.

The graph in Figure 7 illustrates the non-uniformity of the magnetic field as it impacts the angular error. Linearization methods can be applied to compensate for this effect.

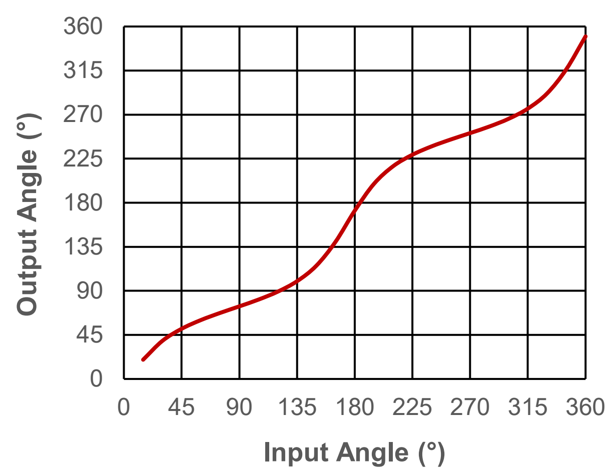

Figure 7. Off-shaft non-linearity.

3.3 Linear Sensing

The CT300 can be used for temperature independent linear position sensing.

Typically, for a linear position application, a linear magnetic sensor can be used (refer to Crocus Technology's CT100). However, as will be explained in this application note, all magnets have a temperature coefficient. This means that the magnetic field strength of the magnet will change due to temperature variation, which then 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 low temperature coefficient magnets that are typically more onerous and costlier.

The CT300 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 Gauss).

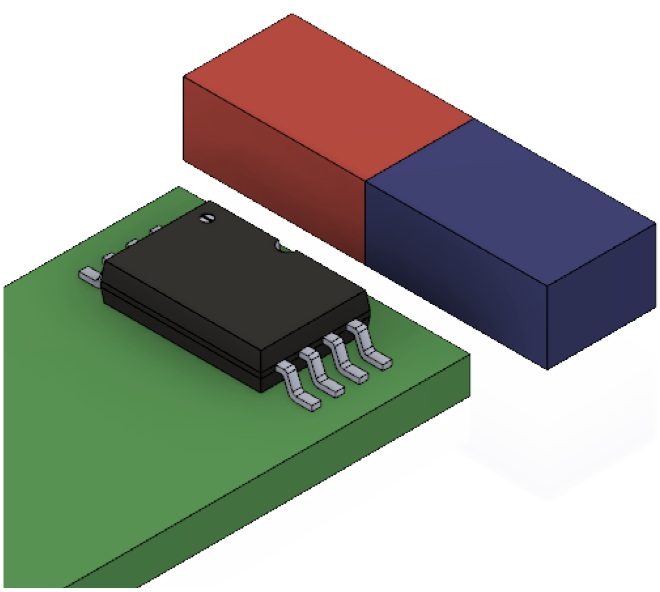

Figure 8. Shows how to mount the CT300 and a bar magnet for a linear movement detection application.

4 MAGNET CONFIGURATION

4.1 Introduction

Magnets come in different shapes, sizes and materials. This application note does not cover a detailed analysis of the performance of the CT300 under different magnets. However, the application note provides a general overview and basic recommendations to allow a design engineer to start using the CT300 with their magnets.

4.2 Magnet Material

Readily available magnets fall typically 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 affects 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 (TempCo) 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.

The table below compares the main found types of magnet materials.

Material	Material Name	B_r	TempCo
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

Table 1. Overview of parameters of widely available magnetic materials.

Note that the values listed in Table 1 are for reference, both the B_r and TempCo can be tweaked by magnet manufacturers. Please refer to the magnet's datasheet from the manufacturer for the exact magnet specifications and proprieties.

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

4.3 Magnet shape

The shape of the magnet does not impact the performance of the CT300 as long as it's under a full 360° rotation, then the magnet generates a homogenous field.

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

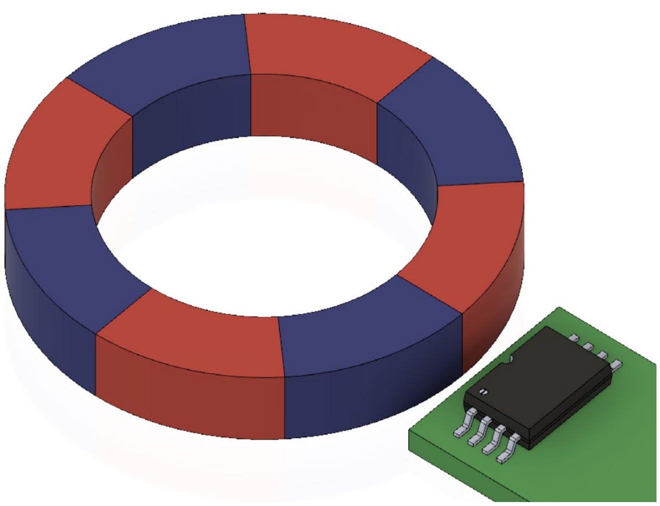

Figure 9. Representation of a side-shaft mounting of a six-pole ring magnet.

4.4 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.
- The magnet's material and build quality
- The angle sensor's intrinsic linearity error.

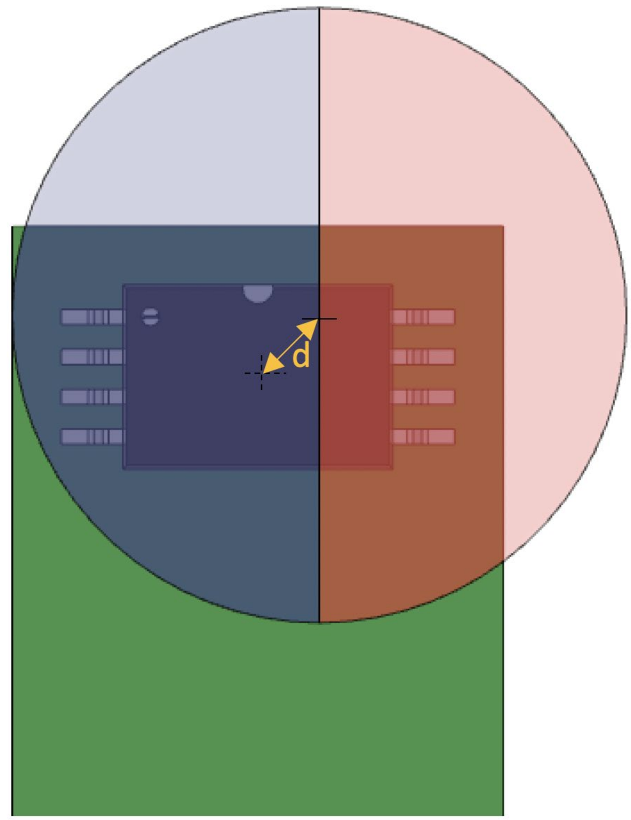

Figure 10. Top view of the CT300 and an on-shaft mounted magnet showing a misalignment by a distance of "d".

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 by using large diameter magnets.

The graph in Figure 11 shows the change in angular error when the magnet is misaligned. The magnet used for this test is a standard N42 NdFeB with dimensions of a 20 mm diameter and a 9.5 mm thickness.

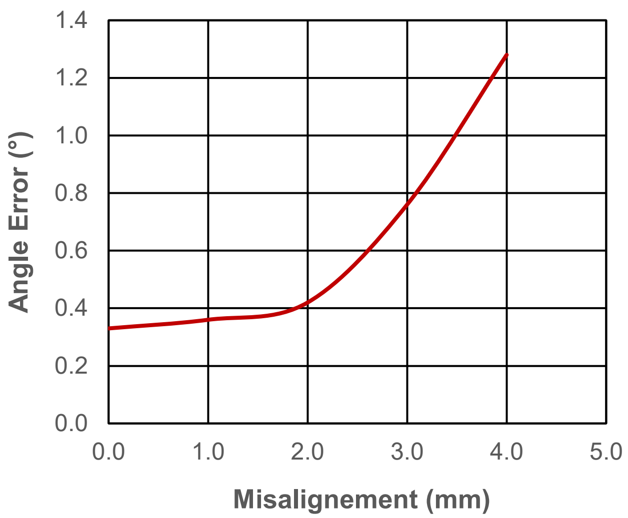

Figure 11. Shows the evolution of the CT300 calculated angular error when the magnet is misaligned by different distances.

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 CT300. The relationship between the magnetic field strength and air gap is shown in Figure 12 below. The magnet used for this analysis is a standard N42 NdFeB with a 20 mm diameter by 9.5 mm thickness.

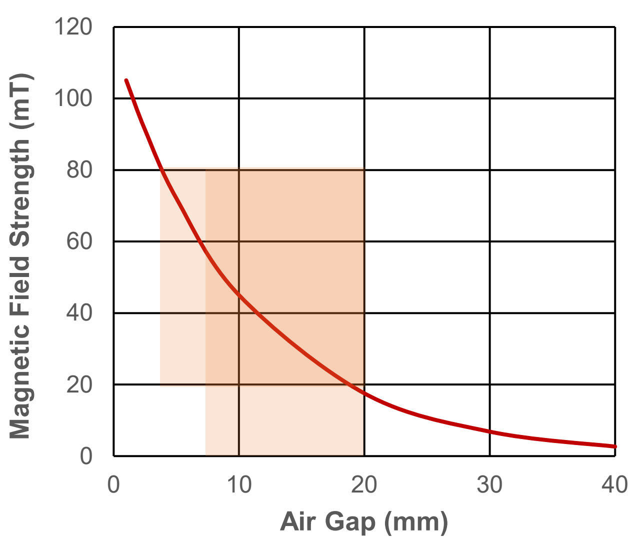

Figure 12. Represents the typical magnetic field strength decay vs. different distances (air gaps).

5 SENSOR PERFORMANCE

The CT300 sensor achieves excellent angular accuracy. Moreover, the inherent benefits of Crocus Technology's proprietary TMR enables an easier implementation of the CT300.

Below is a review of the main performance metrics needed by designers to implement the CT300 sensor.

5.1 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.

5.1.1 Size of the 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 CT300 total sensitive area is 300 × 300 µm. The small size allows for the use of very small diameter magnets and improves the accuracy of the angle measuring system.

5.1.2 Location of the 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 will inherently yield inferior performance.

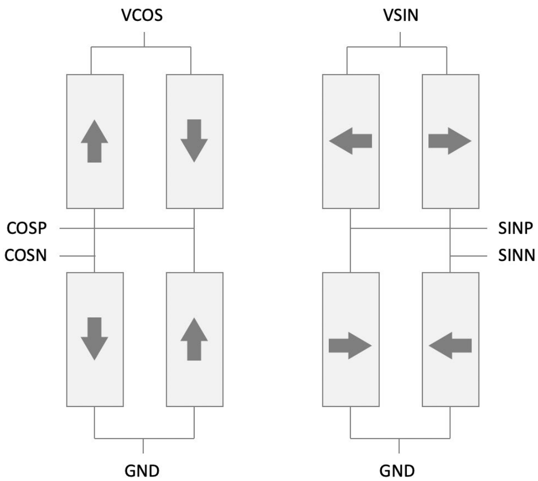

Figure 13. Typical representation of an angle sensor including two Wheatstone bridges.

The CT300 consists of two Wheatstone bridges, each consisting of four (4) TMR elements where each TMR element is comprised of multiple TMR junctions. Crocus Technology's TMR process and fixed layer programming IP 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 CT300 to physically mix the X and Y sensing elements to further improve the performance.

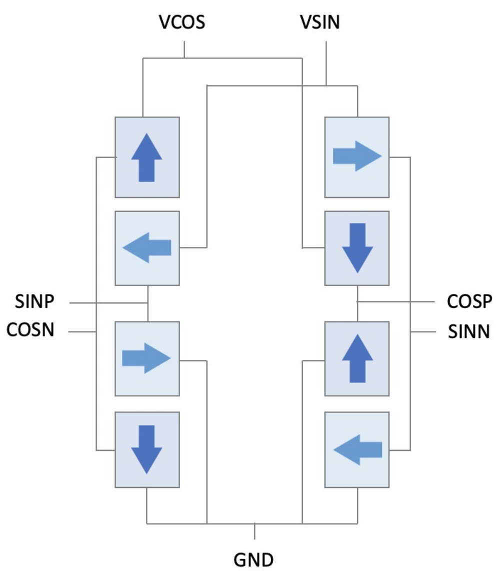

Figure 14. Represents a closer representation of the actual magnetic configuration of the CT300.

5.2 Not a Linear Sensor

The goal of an angle sensor's 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 CT300 is 20 mT to 80 mT and this range guarantees that the CT300's TMR junctions are in saturation. Increasing the magnetic field strength will not yield a different voltage output, however, rotating the external field 180° will saturate the TMR junctions in the opposite magnetization. This means, only the angle of the external field allows a change in the voltage output.

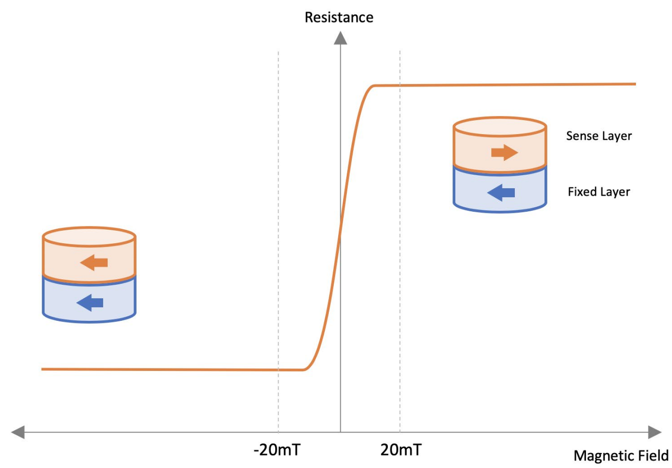

Figure 15. Shows the linear and saturation regions of a typical TMR junction.

More about the behavior of the TMR junctions used in the CT300 can be found in AN119.

5.3 Amplitude Synchronism

Amplitude matching (or amplitude synchronism) describes how identical is the SINE and COSINE outputs 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.

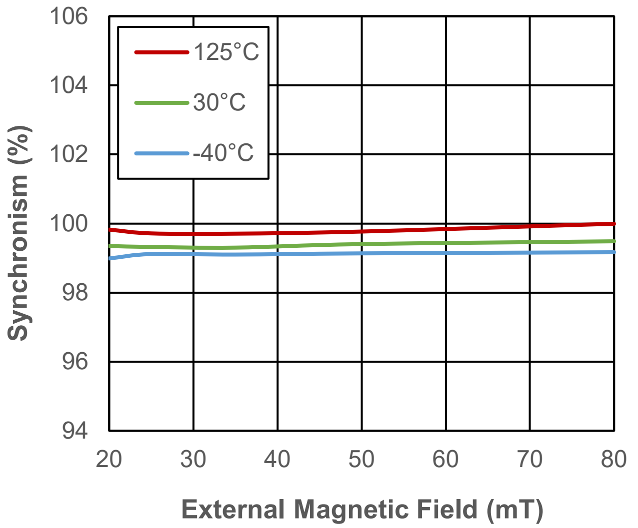

Figure 16. Amplitude matching over different fields and temperatures.

5.4 Single Die

Many of the above stated parameters can only be achieved using a monolithic solution. Temperature behavior, synchronism, offset and the total size of the sensor are positively impacted by the monolithic design of the CT300.

5.5 Temperature

The change of the CT300 parameters over temperature was of major importance during the development of the CT300. This section is a general overview of the change of different parameters over temperature.

5.5.1 Angular Error

Angular error is defined by the difference between the position of the magnet $InputAngle(°)$ and the calculated output $OutAngle(°)$ from the CT300.

$$Error(°) = OutAngle(°) - InputAngle(°)$$

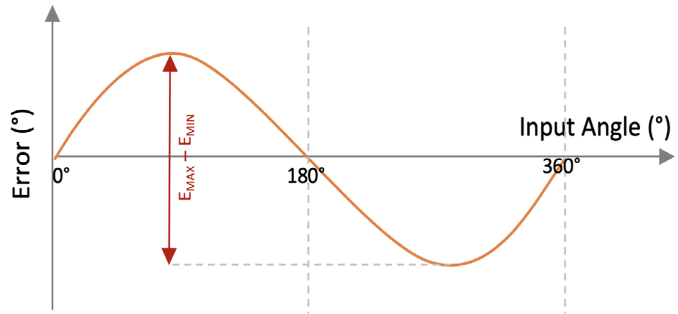

Figure 17. Angular error representation.

The amplitude of the deviation from a perfect straight line between 0° and 360°.

$$Angle\ Error = \frac{E_{MAX} - E_{MIN}}{2}$$

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

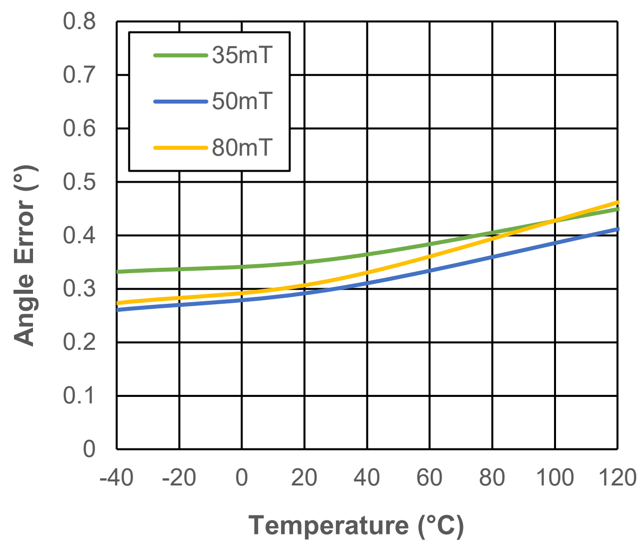

Figure 18. Angular Error over different fields and temperatures.

5.5.2 Synchronism

Synchronism (i.e. Amplitude Matching) is crucial for the operations and ease of implementation of an angle sensor.

The matching of X and Y bridges for an angle sensor is critical because the angle is effectively the ratio of both output (as will be described further below in this application note).

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

Crocus Technology's TMR and the monolithic nature of the CT300 allows near ideal matching under different magnetic field strengths and over a wide temperature range, thus removing the need for extensive matching circuitry and calibration.

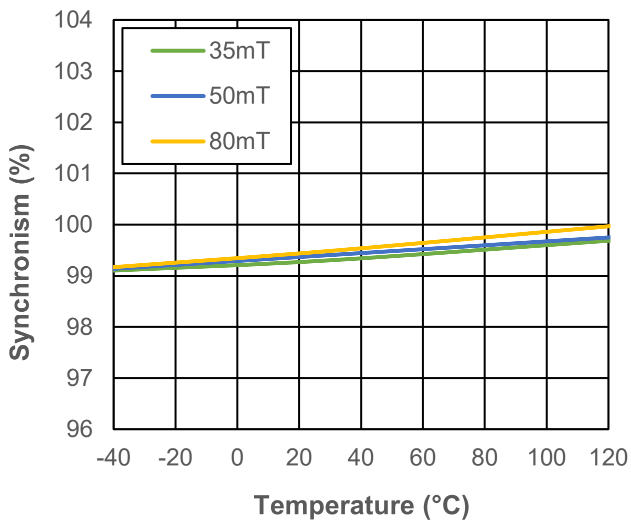

Figure 19. Synchronism over different fields and temperatures.

5.5.3 Offset

Offset is also a major contributor to angular error. Simply calibrating for offset (i.e. subtracting the X and Y offsets) results in overall angular error of less than 1.0°.

The graph in Figure 20 shows the stable performance of offset over a wide temperature range. This allows for easier compensation procedure by simply subtracting the same fixed offset voltage.

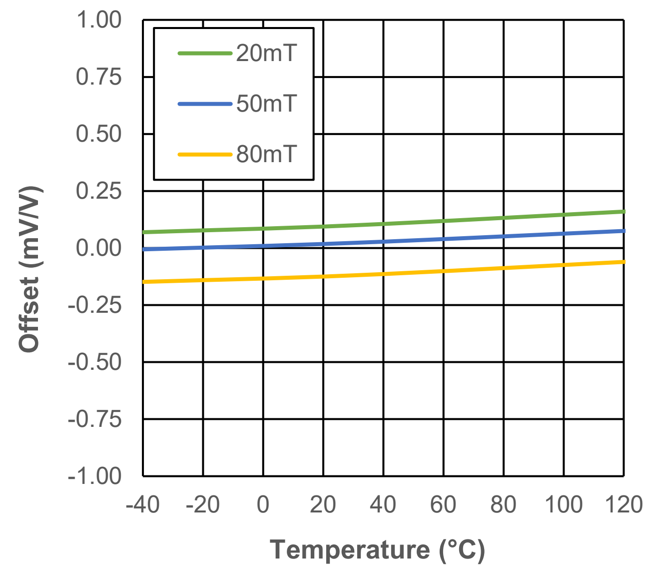

Figure 20. Offset over different fields and temperatures.

5.5.4 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 graph in Figure 21 shows the near ideal performance of the CT300 where orthogonality is not affected by the external magnetic field.

The raw orthogonality of the CT300 is such that the system designer avoids the heavy cost of orthogonality correction. However, for applications where less than 0.3° total angular error is necessary, orthogonality correction is recommended.

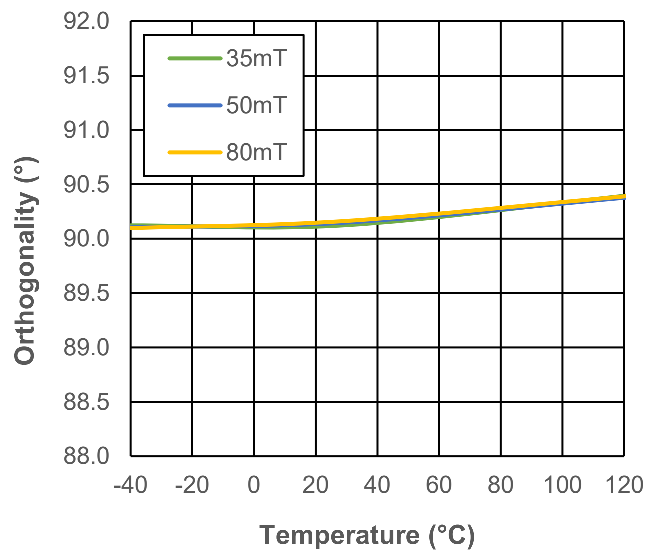

Figure 21. Orthogonality over different fields and temperatures.

6 CALIBRATION PROCEDURE

6.1 No Calibration

The CT300 can be used without any calibration for applications where the absolute angular error is not application critical.

The graphs shown above demonstrate the performance of the CT300 including amplitude matching (i.e. synchronism), offset and orthogonality over different fields and different temperatures.

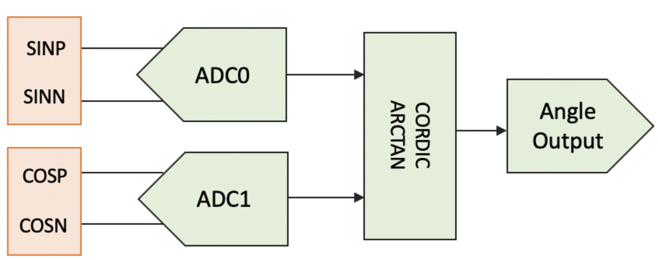

Figure 22. Typical block diagram of voltage sampling and angle calculation.

The block diagram above shows how the CT300 can be connected to an 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 will be described below.

6.2 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 will detail only the offset and amplitude correction. These corrections require simple arithmetic operations by the Microcontroller (MCU).

6.2.1 Offset Correction

The offset of each bridge can be measured using the following equations

$$V_{XOffset} = \frac{V_{XMAX} + V_{XMIN}}{2}$$

$$V_{YOffset} = \frac{V_{YMAX} + V_{YMIN}}{2}$$

Both offset voltages are calculated once after the initial full 360° rotation then stored for the entire operating lifetime of the CT300.

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

6.2.2 Amplitude Correction

The goal of amplitude correction is to correct for the small mismatch of amplitude between the CT300's X and Y bridges by normalizing both output voltages to a value between +1.0 V and -1.0 V.

The amplitude of each bridge can be measured using the following equations:

$$V_{Xamplitude} = \frac{V_{XMAX} - V_{XMIN}}{2}$$

$$V_{Yamplitude} = \frac{V_{YMAX} - V_{YMIN}}{2}$$

Both amplitude voltages are also calculated once after the initial full 360° calibration rotation then stored for the entire operating lifetime of the CT300.

To calculate the normalized values, the following equations are used, where V_X and V_Y are the ADC outputs:

$$V_{Xnorm} = \frac{V_X}{V_{Xamplitude}}$$

$$V_{Ynorm} = \frac{V_Y}{V_{Yamplitude}}$$

6.2.3 Phase Error

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

The CT300 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 CT300. 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, then it will need to convert sequentially X then Y. This error will be greater with higher speed systems (e.g. high RPM motors).

7 ANGLE DECODING PROCEDURE

The CT300 provides two differential analog outputs. Both V_X and V_Y voltages need to be sampled to extract the angle.

Referring to the CT300 datasheet:

$$V_X = V_{COSP} - V_{COSN}$$

$$V_Y = V_{SINP} - V_{SINN}$$

7.1 Differential Input ADCs

The peak-to-peak voltage output of the CT300 is 0.4 mV/V or 1.32 V_{PP} using a 3.3 V supply voltage. This allows the CT300 to be directly connected to an ADC without the need for an amplification stage.

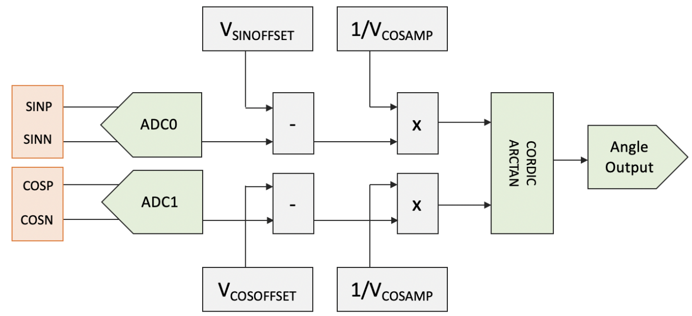

Figure 23. Typical block diagram of voltage sampling and angle calculation with offset compensation and amplitude normalization.

7.2 Single-Ended ADC Inputs

To convert the differential outputs of the CT300 to a single-ended output, the following circuit can be implemented using instrumentation amplifiers. The gain can be adjusted if needed, more importantly the V_{REF} voltage will be set at a new mid-voltage level around which the voltage output will swing. Effectively level-shifting (i.e. offsetting) the output of the CT300 which is described below:

$$V_{XOUT} = V_{REF} \pm V_{XAmplitude}$$
$$V_{YOUT} = V_{REF} \pm V_{YAmplitude}$$

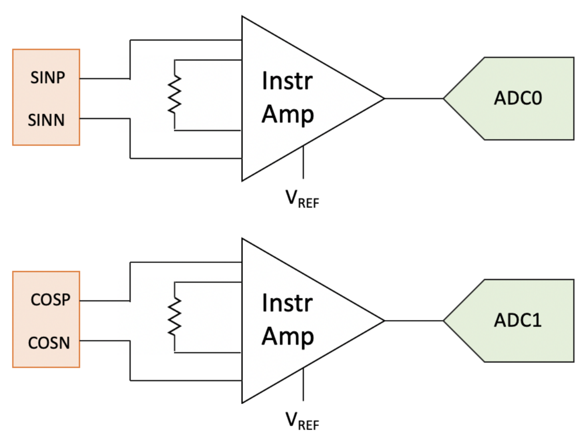

Figure 24. Shows a typical circuit to adjust gain and offset of the CT300 before the ADC stage.

7.3 Calculating the Angle

Once both V_X and V_Y voltages are converted and corrected for very low angular error, the following equation can be solved to extract the angle.

$$\theta = \arctan \cdot 2\left(\frac{V_Y}{V_X}\right) \times \frac{180}{\pi}$$

The equation above will calculate the angle output in a range between [-180°, 180°].

8 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) will yield 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.