Application Note

Achieving Highest System Angle Sensing Accuracy

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ABSTRACT

Motor controlled systems that require precise angle feedback are abundant across many application settings. For instance, autonomous mobile robots (for example, vacuum cleaners, lawnmowers, or warehouse transports) rely on accurate feedback to properly guide the machine to its intended location. Additionally, manufacturing 6-axis robotic arms and collaborative robits (cobots) require precise control to ensure exactness is assembly for improved throughput and optimal quality. In all systems, mechanical alignment tolerances and signal chain factors will contribute to observed measured angle error for magnetic sensors. This report will discuss magnet selection, sensor placement, and how these electrical and mechanical error sources impact measurement. Finally, processes for calibrating angle error will be presented to show how to achieve the optimal angle accuracy for any system.

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1 Introduction

Achieving the highest precision angle measurements in magnetically sensed applications requires consideration of all possible error sources. These various sources may be the result of mechanical imperfections of the system, or may be related to the signal chain of the sensing device. Taking appropriate design steps in consideration of these factors will help produce the highest accuracy result.

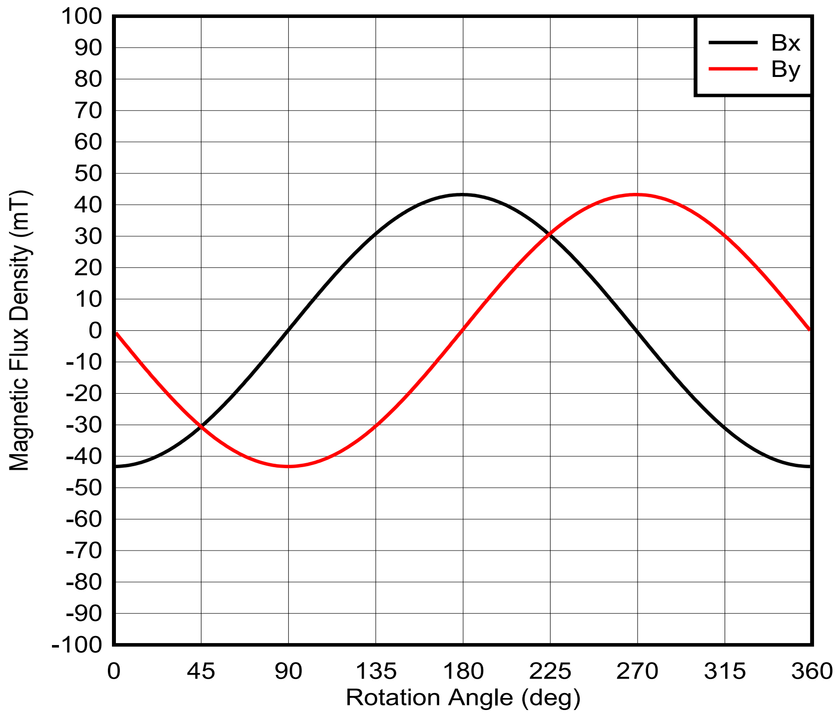

Figure 1-1. Ideal Sine Cosine Arctangent Inputs

Angle is typically measured using sinusoidal inputs 90 degrees out of phase. This sine/cosine relationship allows the use of the arctangent to calculate the final error. This may be achieved using two one dimensional sensors strategically placed with a 90 degree separation about the rotating magnet, or a two or three dimensional sensor may be placed anywhere the magnetic field is sufficiently strong. The separate components of the magnetic field vector will be naturally 90 degrees out of phase, which makes these sensors more ideal for angle detection.

2 Magnet Selection

Of initial important when designing for any angle measurement using magnetic inputs (Hall-effect, AMR, GMR, TMR) is the magnet used as an input source. Depending on the directional sensitivity of the sensor, it will be important to ensure that adequate field inputs are present for the sensor to operate normally.

Consider briefly TMAG5170 or TMAG5273. These devices are linear three dimensional (3D) Hall-effect sensors. TMAG5170 uses an SPI interface, while TMAG5273 communicates using I2C. With sensitivity in all three axes the sensor placement is flexible for either sensor.

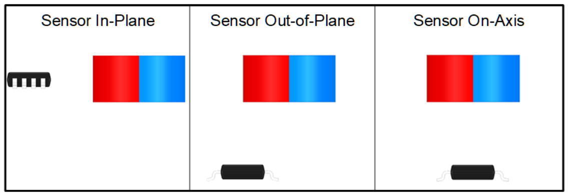

Figure 2-1. Sensor Placement Options

2.1 Placement Considerations

There are a few key considerations to note from the positions shown in Figure 2-2. The On-Axis case is the most ideal location for angle sensing using a single magnetic sensor. In this placement, the field is naturally parallel to the surface of the magnet and will reside entirely within the XY plane of the sensor. To achieve this placement, the diametric magnet is centered on the rotating shaft and the sensor is aligned exactly to the magnet's axis of rotation. This relationship will hold true in this position even when using a magnet with a non-circular profile.

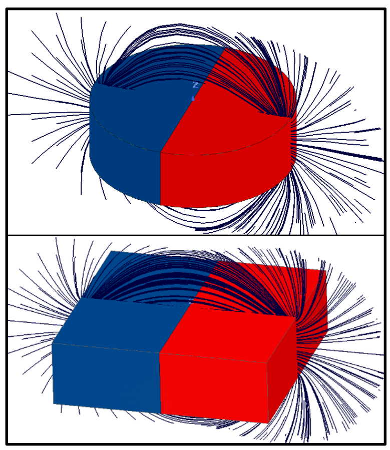

Figure 2-2. Diametric Magnet Field Profiles

While the square faced magnet may be used in this location, it will otherwise not be recommended due to the non-sinusoidal nature of the input magnetic field. The square magnet is useful to help facilitate alignment during assembly of the end product. For any magnet profile, the primary benefit of on-axis alignment is that mechanical errors tend to have a lesser impact on the final angle measurement. This is demonstrated in Section 4.

Another option shown in Figure 2-1 is an In-Plane alignment. This is a very compact alignment option but produces inputs which are significantly mismatched. The resulting amplitude mismatch creates non-linearity of the angle calculation. TMAG5170 and TMAG5273 offer amplitude correction to minimize this effect. This alignment allows a dipole ring magnet to be installed anywhere along the rotating shaft, and this keeps the end of shaft free for use by the rest of the system. In-plane alignment enables angle measurement to be more easily integrated into a BLDC motor with minimal increase to the motor size.

The final placement option is shown as off-axis and represents any other location. Outside of the in-plane and off-axis alignments, there are any number of locations that will produce a measurable field with a component in all three Cartesian directions. The amplitude of each component will vary with location, but will remain sinusoidal and separated in phase from each other by 90 degree intervals. While there are positions which may be found that will produce equally balanced inputs, it should be expected that there will likewise be amplitude mismatch between the two axes used for angle calculation.

2.2 Magnet Properties

Aside from selecting whether or not to use a diametric cylinder for an on-axis measurement or a ring magnet for either off-axis or in-plane measurements, various other magnet properties will influence the magnetic field being observed.

Material Grade

The material grade for any magnet directly influences the B-H relationship of that magnet. It is useful to understand the relationship of the resulting B-field for any magnet as a result of an applied external H-field source.

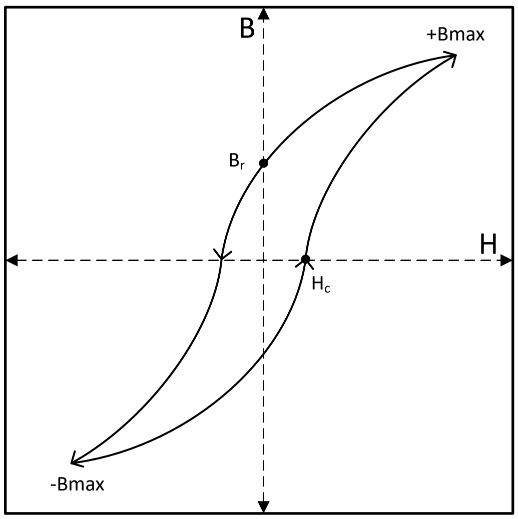

Figure 2-3. Example B-H Curve

When the applied H-field used to magnetize a permanent magnet is removed, the residual B-field value is referred to as remanence, or B_r. This value is measured in a closed magnetic circuit, and is not equivalent to the surface field of the magnet. Surface field is measured in an open magnetic circuit using a magnetometer, and will vary with the magnet geometry. B_r will be constant for any size magnet of the same grade, while the surface field produced by a magnet will depend on the relationship between the surface area and pole length of that magnet.

The various difference grades of any magnetic material will have a different B_r values, which determine the resulting magnetic field strength for that magnet. Consider the relationship between B-field and distance of various grades and materials of magnets with equal dimensions shown in Figure 2-5. With the sensor placed along the axis of polarization of the magnet, it is possible to adjust range to find the peak B-field value which will be observed during rotation. For this case and all following plots, a magnet which has a diameter of 6 mm and a thickness of 3 mm will be used.

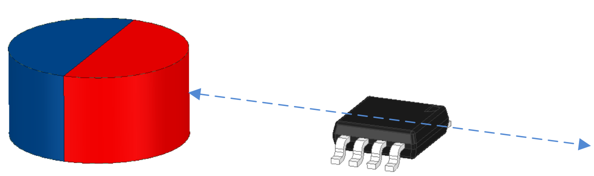

Figure 2-4. Airgap Range of Magnet and Sensor

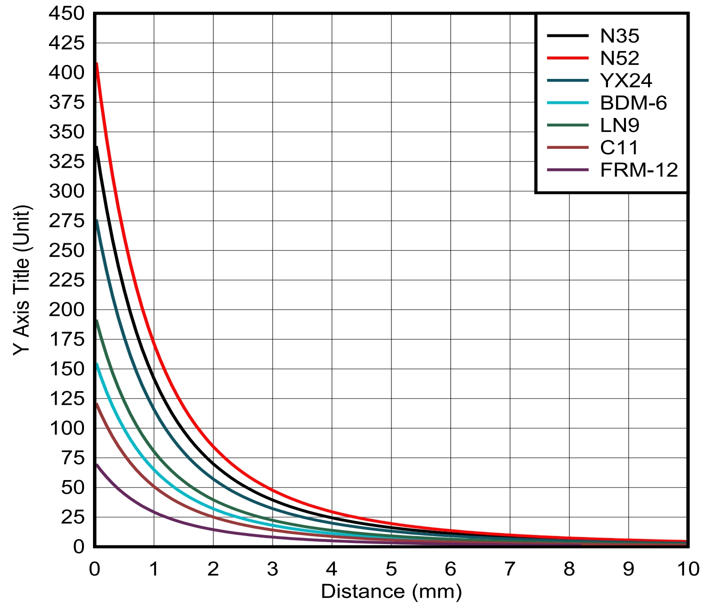

Figure 2-5. Peak Field Magnitude vs. Airgap Distance for Various Magnet Materials

Size

As mentioned in Material Grade, the size of the magnet will influence the surface magnetic flux density, and resulting measured field for any given magnet. Consider the relationship of B-field vs. Distance for various N52 grade neodymium magnets whose height and radius are equal shown in Figure 2-6.

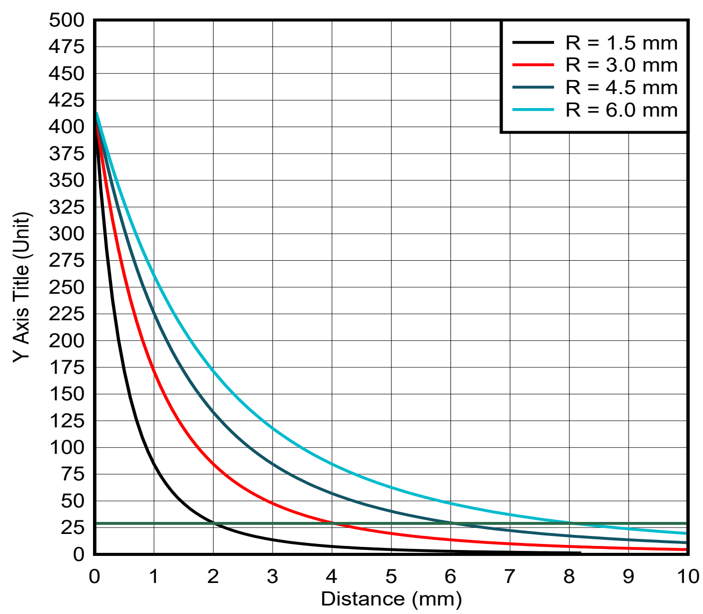

Figure 2-6. Peak Field Magnitude vs. Airgap Distance for Various Magnet Radius

Notice that the surface field is equivalent for each magnet, and the observed field at any air gap distance is greater for a larger magnet radius. What is also interesting to note, is that the ratio of the field observed at any distance to the radius of the magnet remains constant. That is, the field observed at 2 mm using the 1.5 mm radius magnet is equivalent to the field at 8 mm using the 6 mm magnet radius.

Temperature Drift

The various magnetic materials available all have differing responses to variations in temperature. For all magnets, the magnetic field strength will reduce by some value up until the Curie temperature, where the atomic dipoles within the magnet can no longer retain magnetic alignment. The typical value for various magnet materials is shown in Table 2-1

Table 2-1. Magnetic Material Temperature Response

Material	Temperature Drift (C)
NdFeB	-0.12%/C
SmCo	-0.04%/C
AlNiCo	-0.02%/C
Ferrite	-0.2%/C

For systems with a wide operating temperature range, Samarium Cobolt (SmCo) type magnets are often selected for their low temperature drift, although they do not offer as strong of a field typically observed with Neodymium magnets.

Ultimately for most applications, the goal will be to use the smallest magnet available that can produce a measurable input for the sensor. For any system, the ability to mount the magnet to a rotating shaft, cost and availability might be the dominant factors in magnet selection. Neodymium magnets (NdFeB) tend to offer the highest magnetic field strength while ferrite magnets tend to be the lowest cost.

3 Measurement Non-Linearity

Beyond the material properties of the magnet that will influence the strength of the field, mechanical misalignments and tolerances may result with non-linearity in angle calculations.

At a high level, the end error results that will be observed fall into four main categories. These each have a direct impact on the linearity of the measurement and need to be managed appropriately to minimize final angle error. These are:

- Amplitude Mismatch
- Offset
- Phase Error
- Distortion

Amplitude Mismatch

Amplitude mismatch is the dominant factor which will influence accuracy. When plotting the separate inputs against each other, it is possible to compare against the ideal unit circle.

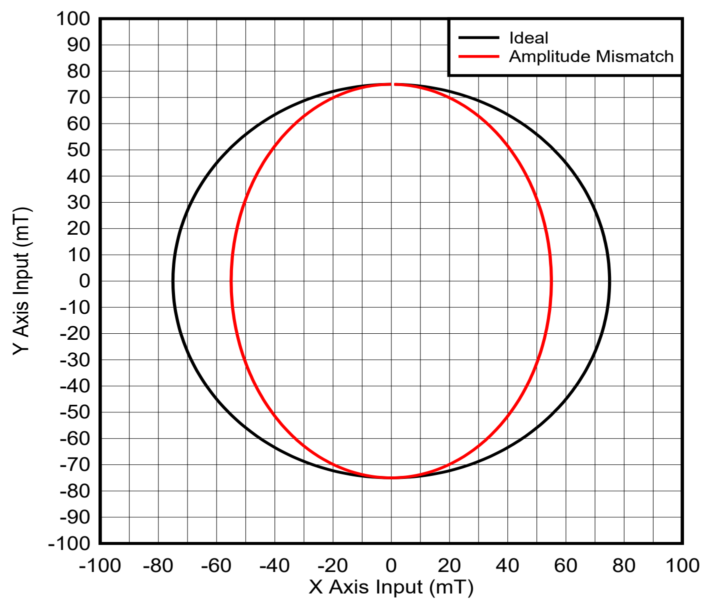

Figure 3-1. Amplitude Mismatch Non-Linearity

Notice that at the axis crossings, the error will be zero. At points in between, the error may become quite significant. This is typically managed by applying a normalization factor to either of the two input sources. Either the amplitude of the larger input may be attenuated, or the amplitude of the smaller input may require an increase in gain. This function is integrated into both TMAG5170 and TMAG5273 to assist with system calibration.

Offset

Input referred offset results with inputs not centered about zero. This imbalance results with the unit circle not being properly centered.

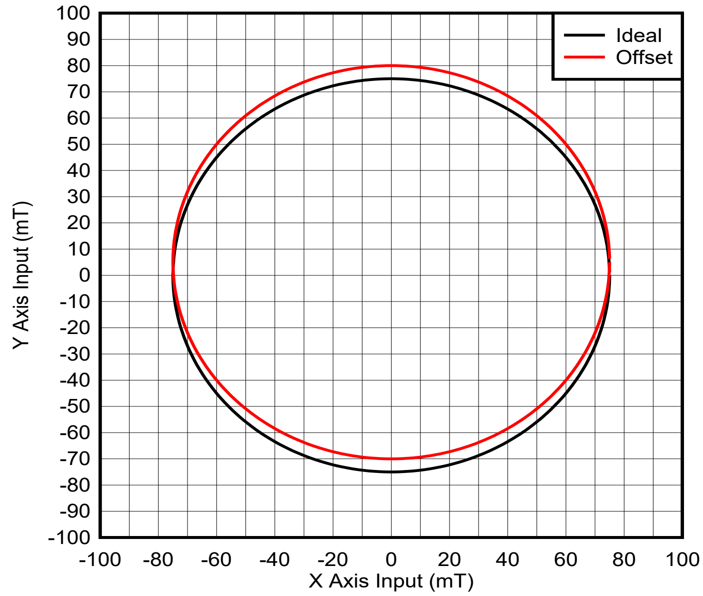

Figure 3-2. Offset Non-Linearity

Phase Error

Phase error between the two inputs used for arctangent calculations results from the inputs being out of phase by more or less than 90 degrees. Combined together, the resulting plot of these inputs appears similar to the amplitude mismatch case, but is not skewed along either axis.

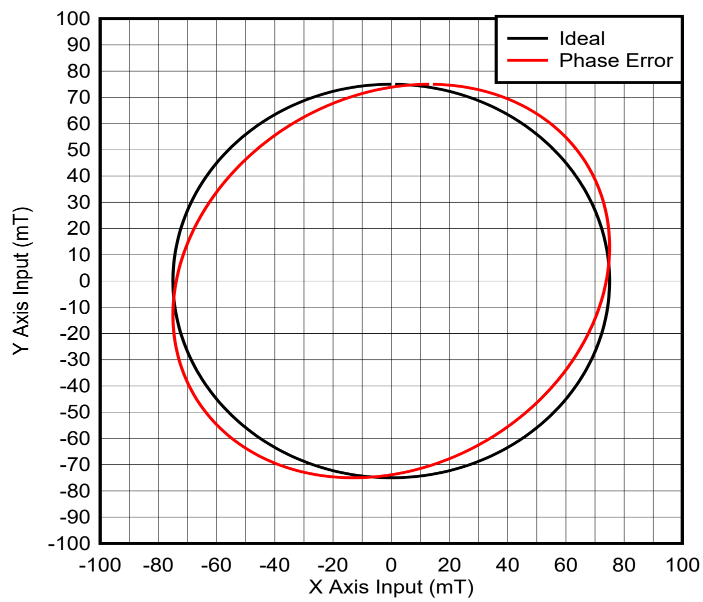

Figure 3-3. Phase Error Non-Linearity

Distortion

Distortion is the result of the magnetic inputs being sensed not being purely sinusoidal. This may result from various factors such as inconsistent range to the magnet or irregularities in magnet shape. For instance, rotating a non-circular magnet or varying the distance to the sensor may produce inputs with a more complex non-linearity.

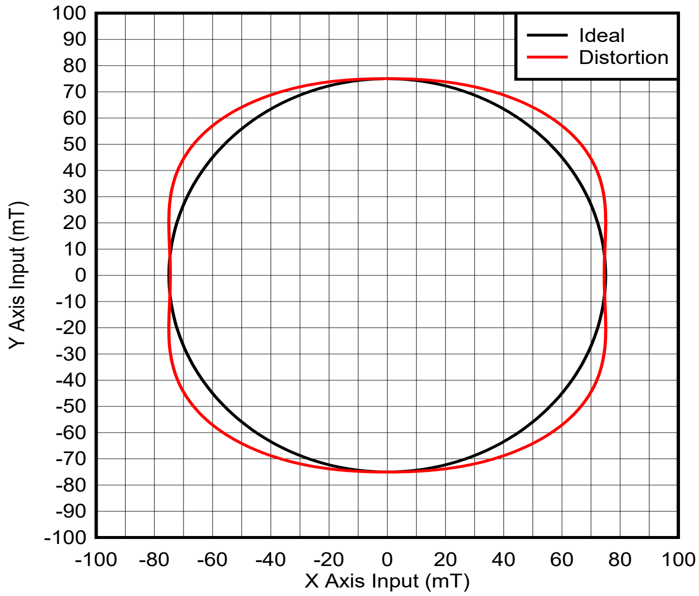

Figure 3-4. Input Distortion Non-Linearity

4 Mechanical Error Sources

The various non-linearities are typical byproducts of system level mechanical errors. These typically are caused by assembly tolerances and produce various combinations of the previously discussed patterns.

These errors may be the results of any of the following conditions:

- Magnet tilt and wobble
- Magnet eccentricity
- Sensor alignment
- Sensor placement offset

What will be evident, is that for any configuration, it will be beneficial to limit manufacturing variances in order to achieve consistent performance across all systems.

These errors will be individually simulated using a magnet which has a diameter of 6 mm and a thickness of 3 mm. Sensor position will be 4 mm from the nearest magnet face for either in-plane or on-axis alignment. For off-axis alignment, the sensor will be placed immediately 4 mm below the outer diameter of the magnet. The magnet grade will be N52.

Magnet Tilt

Errors involved with the orthogonality of the magnet installation on the motor shaft produce an alignment that is tilted when at rest.

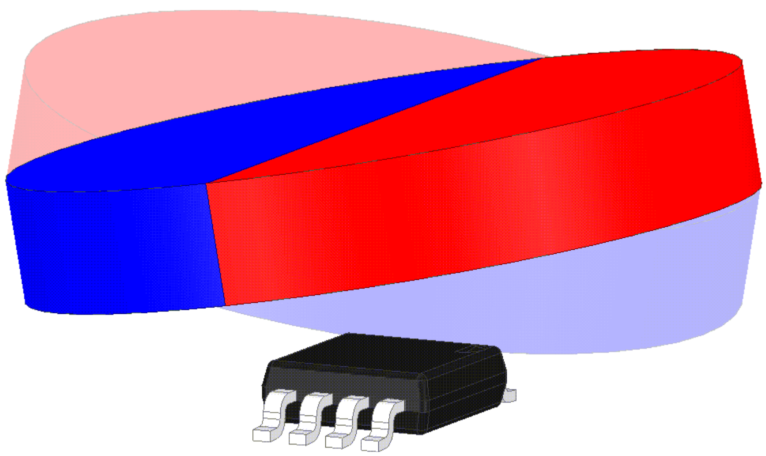

Figure 4-1. On-Axis Alignment with Magnet Tilt

This tilt follows the motor shaft during rotation causing a wobble behavior. The resulting non-linearity will depend on the severity of the tilt and the sensor location. For comparison Figure 4-2– Figure 4-7 show this impact and the resulting angle error from 2 degrees of magnet tilt for each alignment location. In each case, the displayed angle error resulting from amplitude mismatch or offset have already been corrected, and the residual error is the result of either non ideal phase or input distortion.

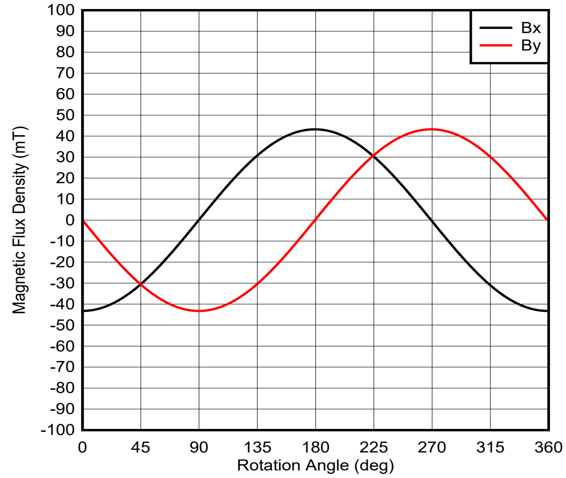

Figure 4-2. On Axis: Magnetic Field Inputs with Magnet Tilt

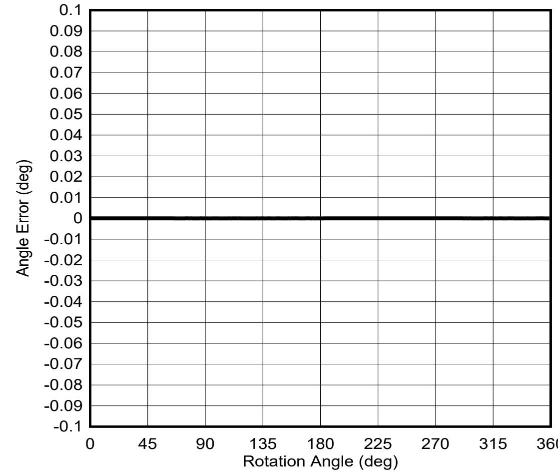

Figure 4-3. On Axis: Angle Error with Magnet Tilt

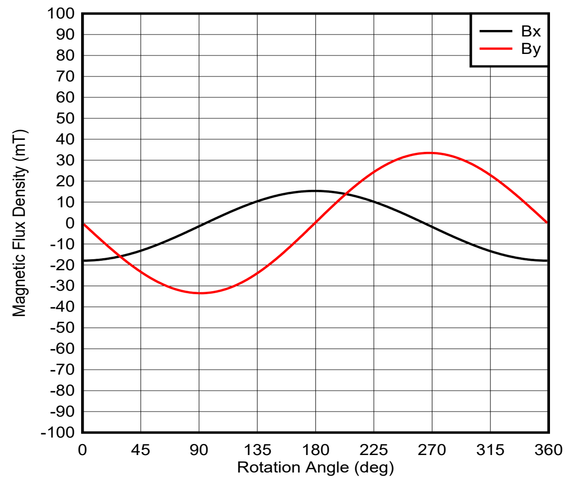

Figure 4-4. Off Axis: Magnetic Field Inputs with Magnet Tilt

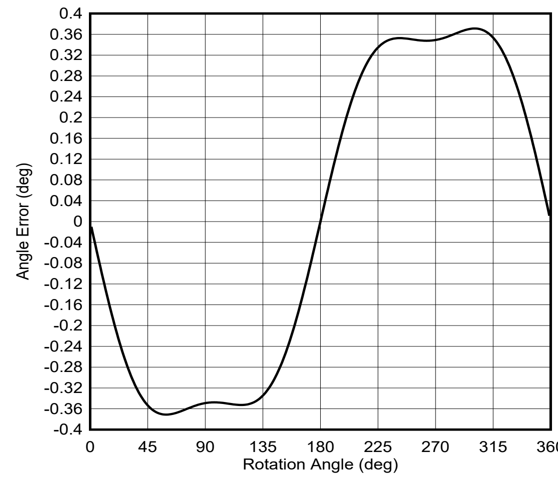

Figure 4-5. Off Axis: Angle Error with Magnet Tilt

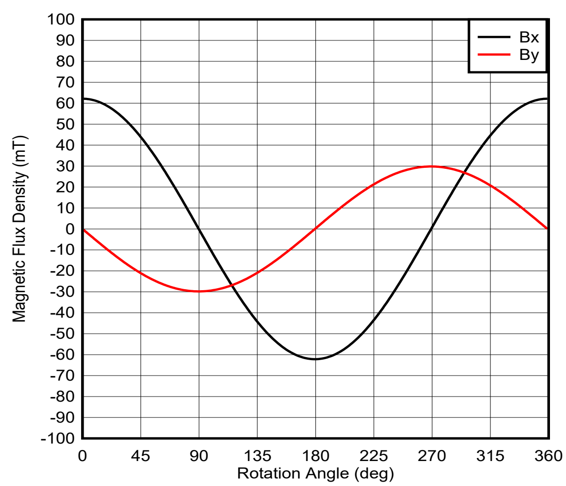

Figure 4-6. In Plane: Magnetic Field Inputs with Magnet Tilt

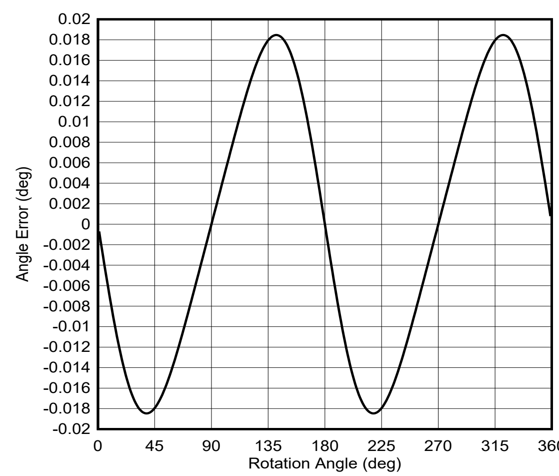

Figure 4-7. In Plane: Angle Error with Magnet Tilt

Magnet Eccentricity

If the magnet is not centered about the rotation axis of the shaft, then a different sort of wobble will emerge.

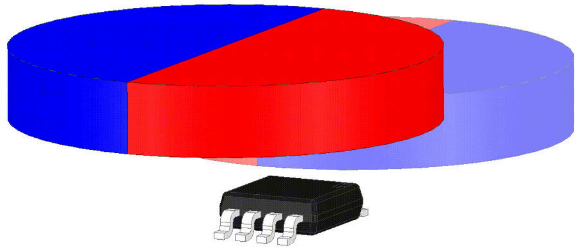

Figure 4-8. On Axis Alignment with Eccentricity

FIGURE of Eccentricity

In this case, the magnet will oscillate within its own plane. The result is an angle dependent magnet location. This error may cause significant angle errors. An offset from center of 0.1 mm produces the following errors. In each case, the displayed angle error resulting from amplitude mismatch or offset have already been corrected, and the residual error is the result of either non ideal phase or input distortion.

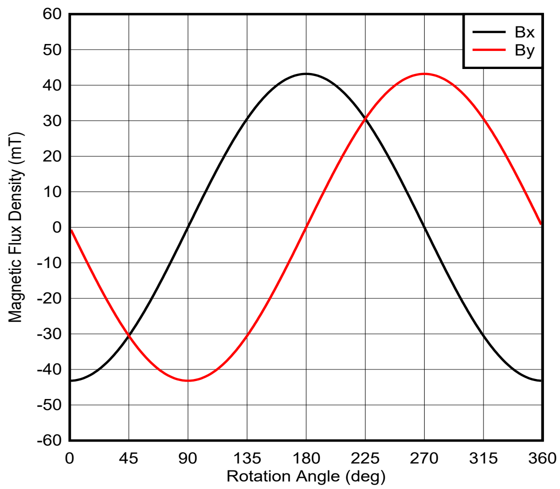

Figure 4-9. On Axis: Magnetic Field Inputs with Eccentricity

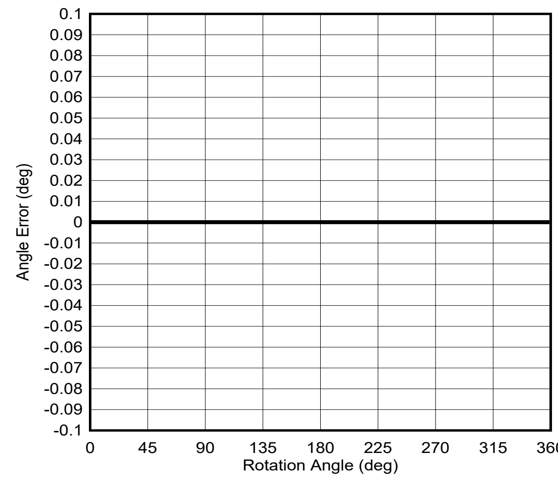

Figure 4-10. On Axis: Angle Error with Eccentricity

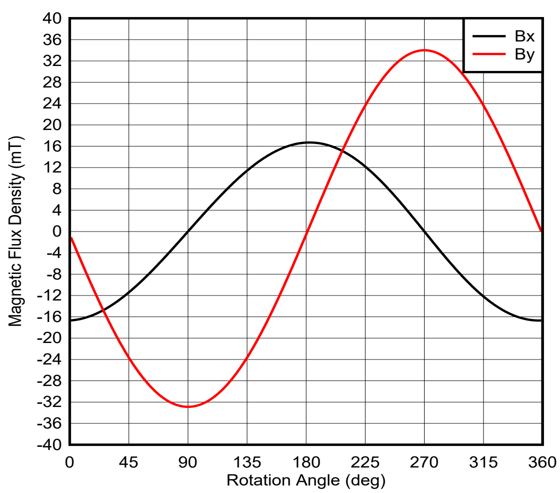

Figure 4-11. Off Axis: Magnetic Field Inputs with Eccentricity

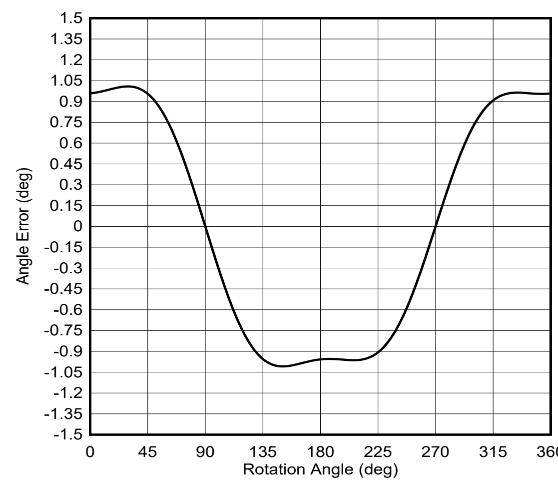

Figure 4-12. Off Axis: Angle Error with Eccentricity

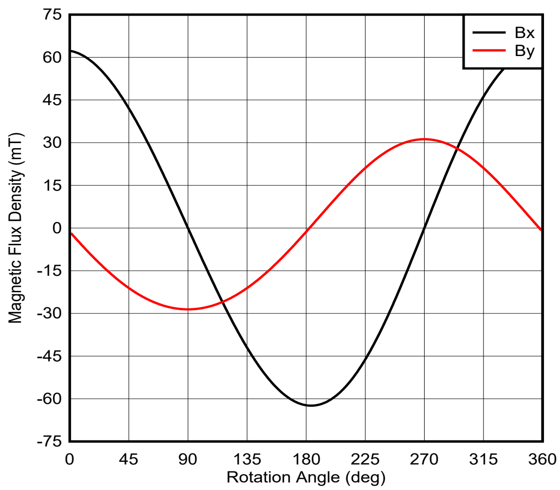

Figure 4-13. In Plane: Magnetic Field Inputs with Eccentricity

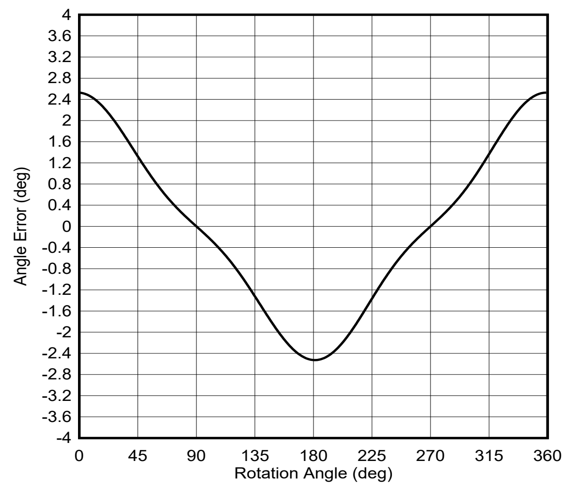

Figure 4-14. In Plane: Angle Error with Eccentricity

Sensor Alignment

Proper system alignment typically requires the sensor to be placed orthogonal to the rotating magnet.

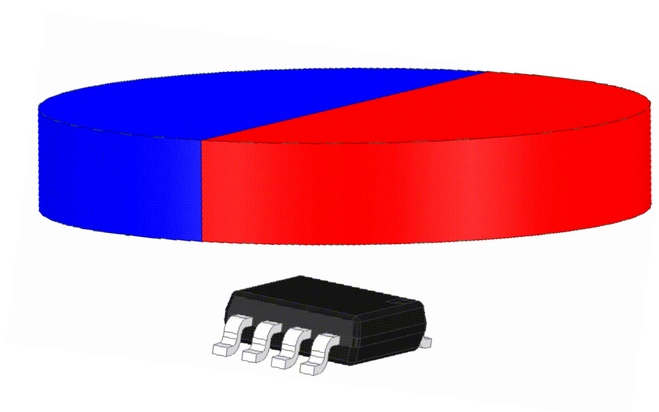

Figure 4-15. On Axis Alignment with Sensor Tilt

This alignment may be impacted by tilt of the rotating shaft, or by tilt of the actual sensor. During solder reflow, many surface mount devices self-align to the PCB footprint and some variability may exist as the solder cures. Rotation by just a few degrees about each axis produces the following errors. In each case, the displayed angle error resulting from amplitude mismatch or offset have already been corrected, and the residual error is the result of either non ideal phase or input distortion.

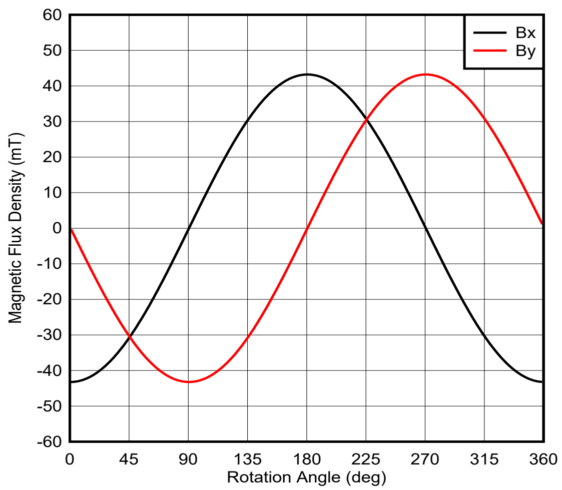

Figure 4-16. On Axis: Magnetic Field Inputs with Sensor Tilt

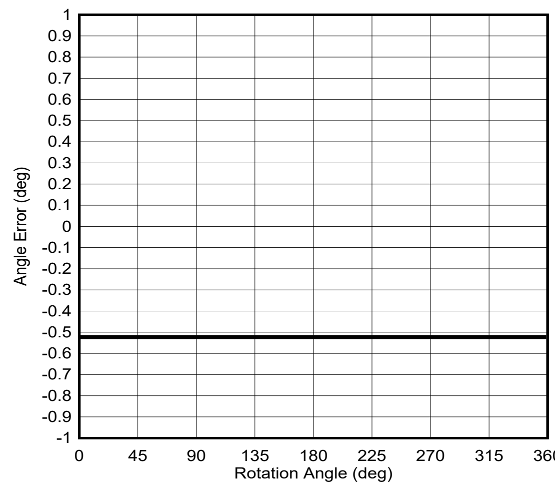

Figure 4-17. On Axis: Angle Error with Sensor Tilt

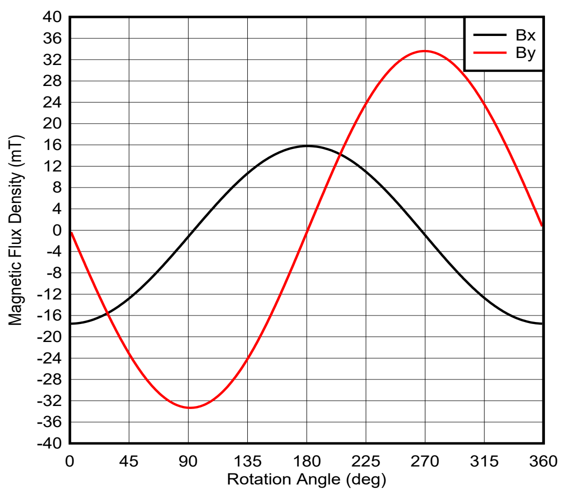

Figure 4-18. Off Axis: Magnetic Field Inputs with Sensor Tilt

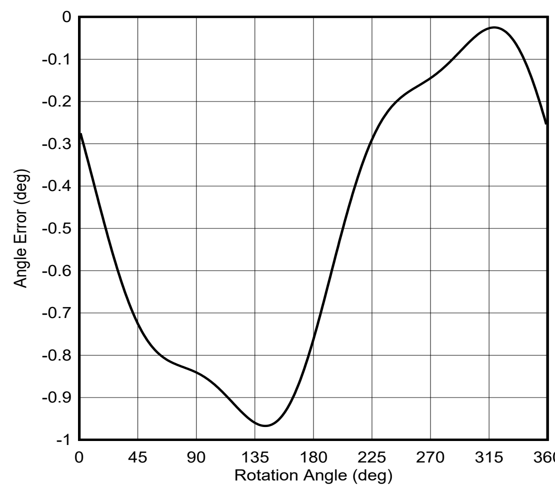

Figure 4-19. Off Axis: Angle Error with Sensor Tilt

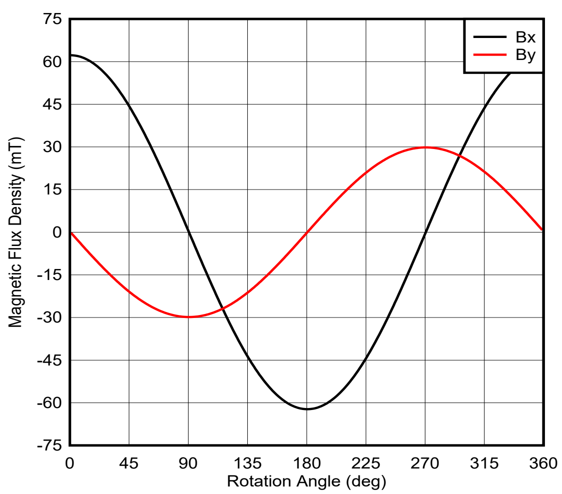

Figure 4-20. In Plane: Magnetic Field Inputs with Sensor Tilt

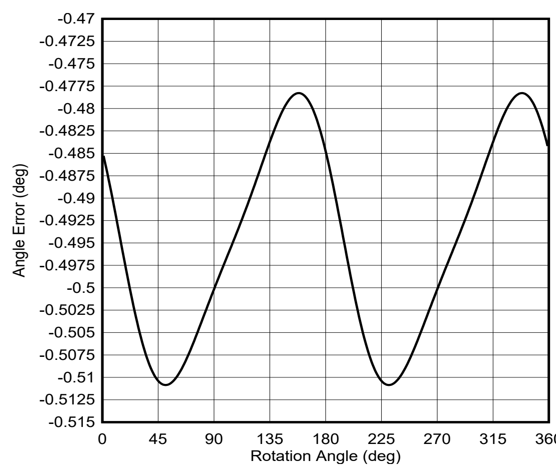

Figure 4-21. In Plane: Angle Error with Sensor Tilt

Sensor Placement Offset

Sensor placement offset is the result of the final sensor location not matching the intended design.

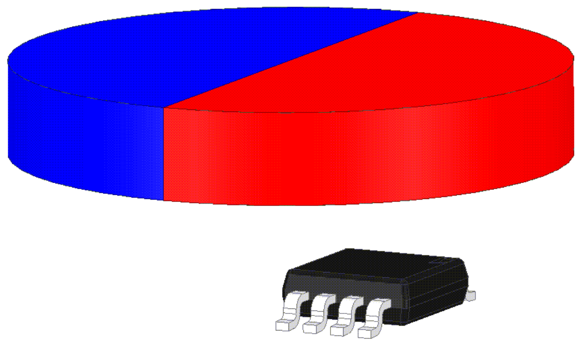

Figure 4-22. On Axis Alignment with Position Offset

This may be the result of assembly challenges from the position the device aligns to during solder reflow to tolerances of system component locations within the larger system. An offset of 0.5 mm in both X and Y directions will produce the following errors. In each case, the displayed angle error resulting from amplitude mismatch or offset have already been corrected, and the residual error is the result of either non ideal phase or input distortion.

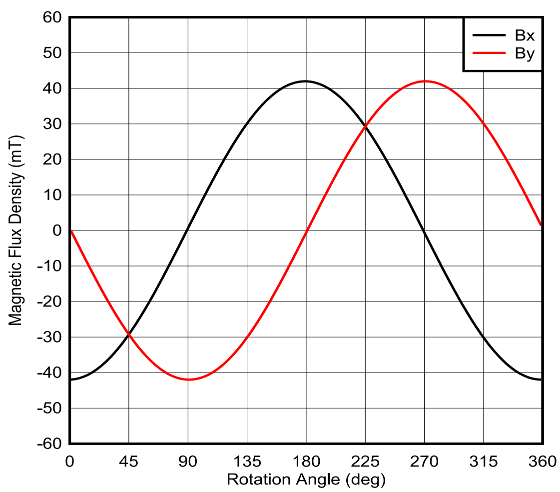

Figure 4-23. On Axis: Magnetic Field Inputs with Position Offset

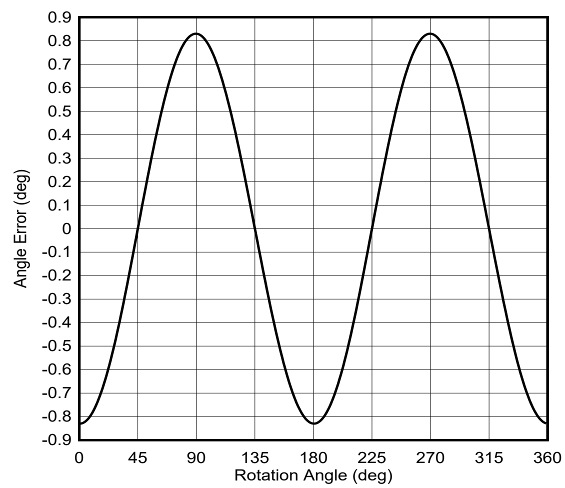

Figure 4-24. On Axis: Angle Error with Position Offset

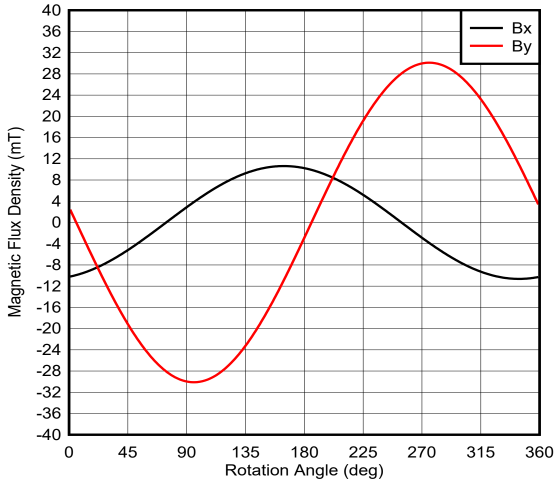

Figure 4-25. Off Axis: Magnetic Field Inputs with Position Offset

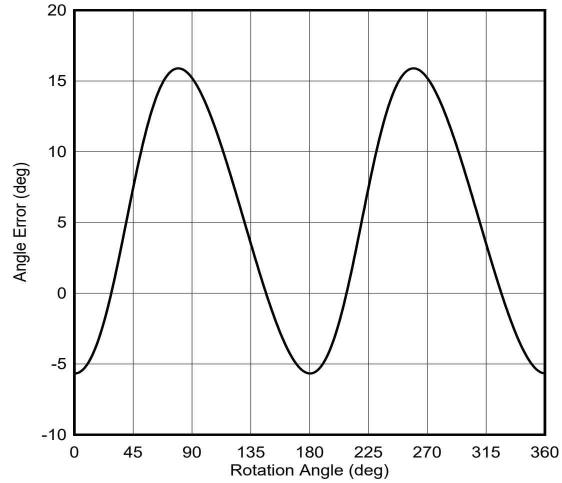

Figure 4-26. Off Axis: Angle Error with Position Offset

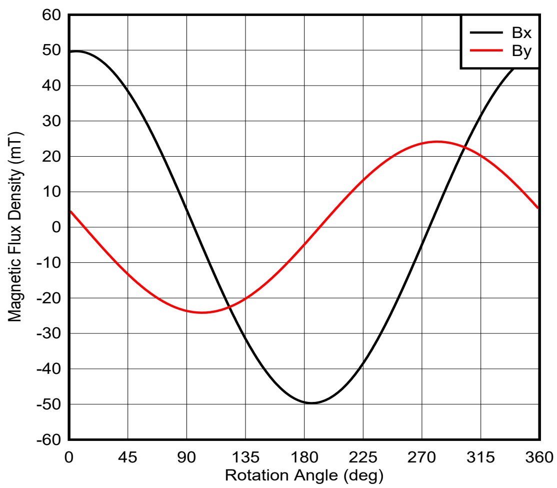

Figure 4-27. In Plane: Magnetic Field Inputs with Position Offset

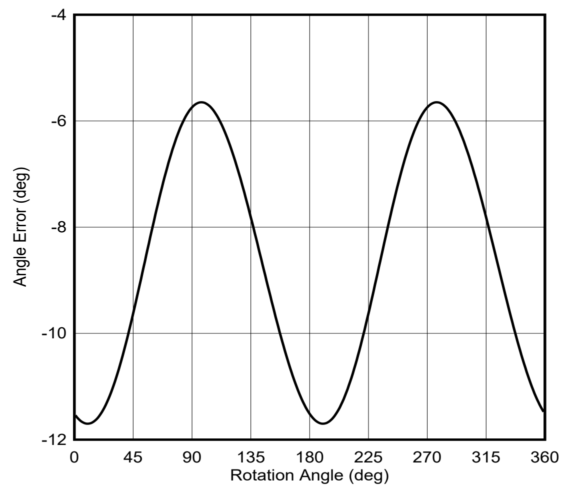

Figure 4-28. In Plane: Angle Error with Position Offset

5 Signal Chain Errors

In addition to the various mechanical errors, signal chain errors may exist that further complicate angle measurements. These factors may play a direct role in the quality of the measurement how the data is used. For linear Hall-effect sensors such as TMAG5170 and TMAG5273 the following parameters should be understood when designing for angle measurements.

Sensitivity Mismatch

As discussed earlier, amplitude mismatch can result in output angle non-linearity. Even in cases where the sensor is perfectly located with an ideal input, it is possible that the sensitivity gain error for each channel may vary somewhat. Small errors between each channel should be corrected using the same method to correct for input amplitude mismatch. That is, a scalar sensitivity gain adjustment should be applied to normalize the two output channels to the same amplitude.

Offset

Input referred offset will present itself as a fixed DC offset to the device output. It will directly create angle error as described in Offset. It is typical to perform an initial sweep with any rotating magnet to correct for this error. Using peak measured values, both sensitivity gain error and input referred offset can be minimized for any system.

Noise

Another key parameter that may impact the angle accuracy is the noise. Considering an RMS input referred noise parameter, this will represent a 1 sigma value. When considering any measurement system, the signal to noise ratio (SNR) will impact the best case resolution possible. When plotting SNR vs peak angle error, the final accuracy will generally follow the trend shown in Figure 5-1

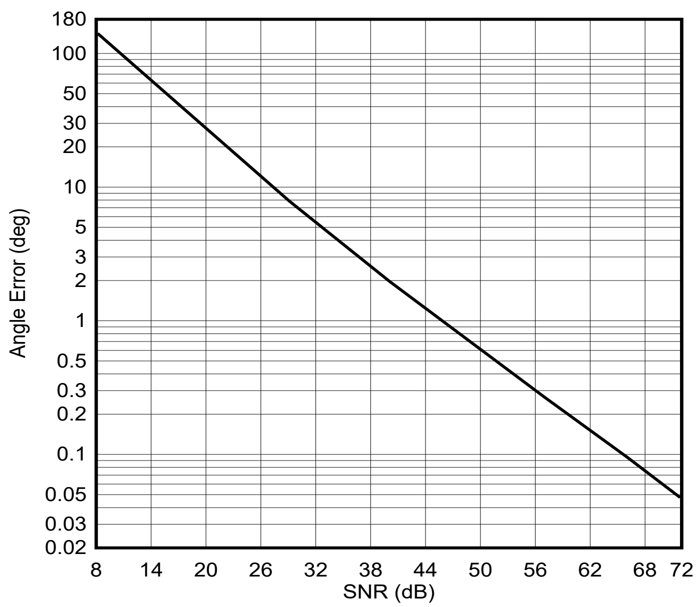

Figure 5-1. Angle Error Resulting from Input Referred Noise

Unless the SNR meets or exceeds the value in this plot, the resulting error in angle calculation may create uncertainty which cannot be corrected for through calibration.

To combat limitations of SNR, a few options are available. Firstly, it is possible to use sample averaging to reduce the input noise by a factor of the square root of the number of samples. TMAG5170 and TMAG5273 offer up to 32x averaging which may be used to achieve a dramatic reduction in noise. This comes with the drawback of an increased sample time, which may cause undesirable delay that can limit maximum sample rates.

The other option would be to adjust the magnet strength or sensor proximity. Each of these options will increase the available magnetic field and improve the SNR of the measurement.

Quantization Error

Quantization error occurs as a result of converting the analog Hall-voltage to a digital using an ADC. The number of available bits in the ADC will set a minimum measurement resolution available to the microcontroller. For any given sample the typical maximum error will be less than or equal to 1/2 LSB. For demonstration purposes, the angle error using a full scale input into an 8-bit ADC is compared to the angle quantization error of a 12-bit ADC in Figure 5-2 and Figure 5-3.

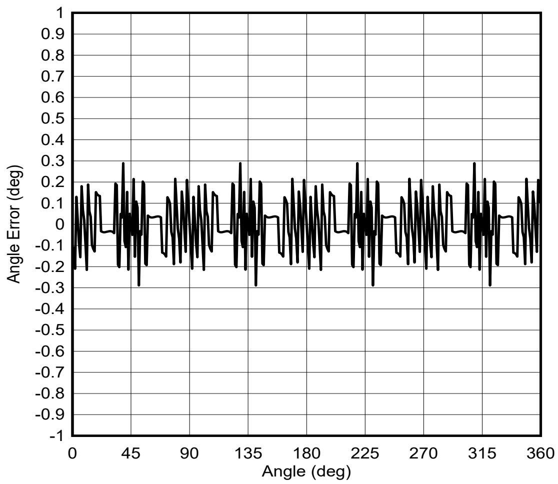

Figure 5-2. 8-bit Quantization Error

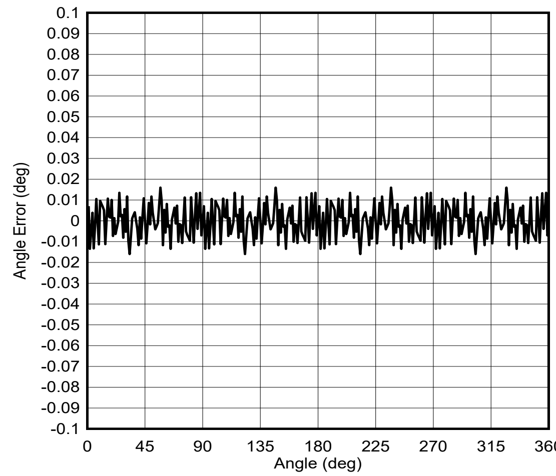

Figure 5-3. 12-bit Quantization Error

TMAG5170 has an integrated 12-bit ADC and is able to return averaged results using a 16-bit output word length.

Propagation Delay

For any magnetic sensing application to determine position of a moving target, it is important to consider propagation delay of the sensor. The feedback to the microcontroller will be received by the microcontroller after some time and motion will continue uninterrupted in that time. Because of this, the measured angle of the rotating magnet will have some fixed phase delay that varies based on the conversion time of the sensor.

When the speed of the motor is known, this information may be used along with the sample rate of the sensor to calculate the change of position of the magnet during the conversion.

TMAG5170 and TAMG5273 allows for a customizable sampling pattern as well as averaging. This creates a variable propagation delay. Complete timing information is located in the data sheet. As an example the expected delay for various averaging modes using the XYX sample pattern are shown in Figure 5-4

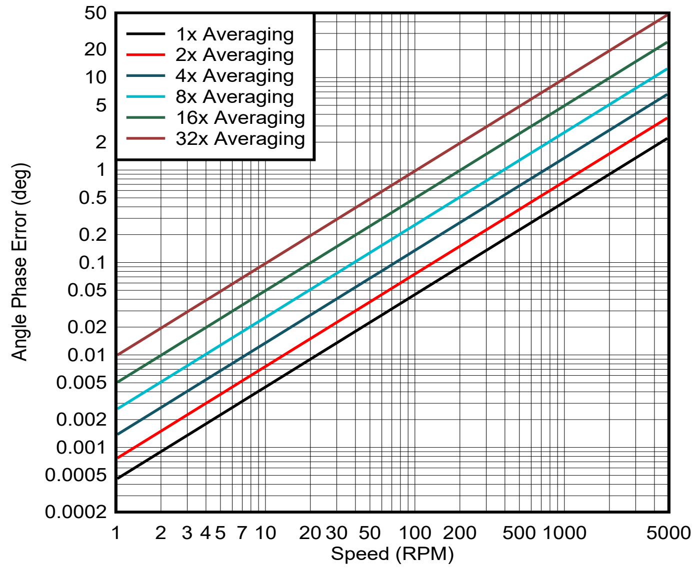

Figure 5-4. TMAG5170 Angle Phase Error vs. Rotation Speed

A critical step in establishing a quality measurement will be to use a deterministic measurement scheme. This can be accomplished using the trigger modes of TMAG5170 and TMAG5273. Triggering the conversion to start at a known time will allow for the most accurate association of the output result to the actual magnet position.

Temperature Drift

As was discussed in Temperature Drift the magnetic field of any magnet is subject to vary with temperature. This can create certain challenges for measurement. TMAG5170 and TMAG5273 both offer programmable temperature compensation to allow the sensor to adjust to these changes in the magnetic field strength. Settings of 0.12%/C, 0.2%/c, and 0 are available to help accommodate most magnet configurations.

Additional Signal Chain Errors

When considering other magnetic solutions, it is additionally important to evaluate the impact of other error sources such as magnetic hysteresis and cross-axis sensitivity, which do not significantly affect TMAG5170 or TMAG5273. These factors tend to be more common in devices utilizing integrated magnetic concentrators or magneto-resistive sensors such as GMR or TMR.

Magnetic hysteresis is the result of having applied a magnetic field to a ferromagnetic material. Similar to the behavior shown in Figure 2-3, there will be some residual magnetization of the concentrator depending on the prior state of the magnetic field from the permanent magnet. As a result, angle measurements depend on the previous position of the magnet, and there will be differences to the observed input with a clockwise rotation of the magnet vs a counter clockwise rotation.

Cross-axis sensitivity is the result of some portion of one magnetic field channel being coupled into the measurement for another axis. This will produce some underlying non-linearity that is dependent on the state of the other channel. Removing this error from measurement requires a complex calibration routine.

6 Calibration Methods

To combat the non-linearities which are unique to any system, it is often necessary to implement calibration to ensure the highest precision results. While efforts to address mechanical or electrical errors prior to performing the arctangent calculation will produce the most linear results, often it is not practical to address each error source individually. Rather, a final profile may be created measuring against a known angle. The error is subtracted from the measured angle to minimize the final position error to be used by the microcontroller. Consider the possible angle error which results from combining the impact of each of the various mechanical error modes. While normally the On-Axis case shows little to no error, when these factors are combined a complex error pattern will emerge. It is worth noting in Figure 6-1 that the cyclical amplitude varies during one full rotation.

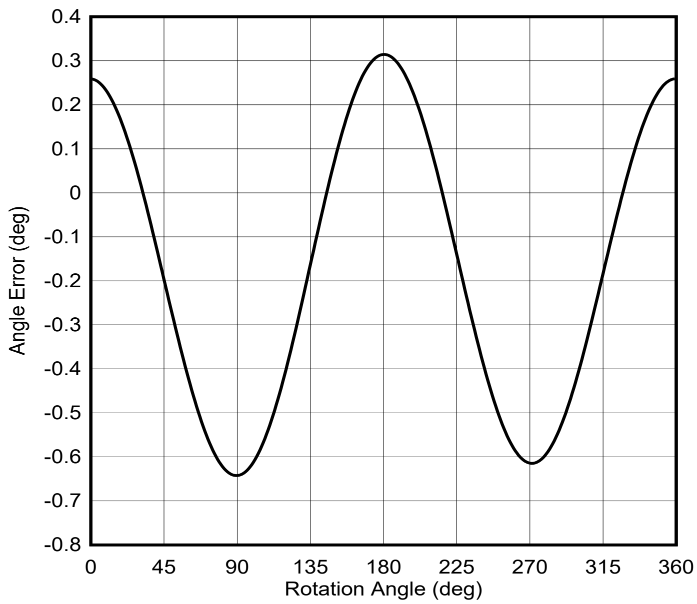

Figure 6-1. On Axis Angle Error with Combined Mechanical Errors

Two approaches are common for calibrating angle measurement errors such as this. The first uses a multi-point lookup table to generate a piecewise approximation of the error curve. As the number of data points increases, the resulting plot will quickly approach the actual system error. Consider this comparison of 8, 16, and 32 point calibrations of an example error curve.

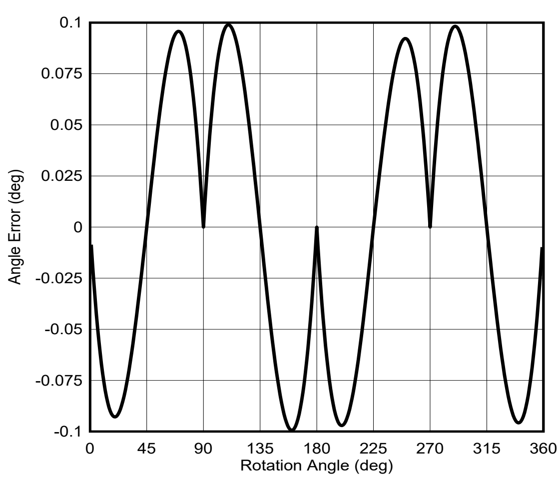

Figure 6-2. 8-point Linearization

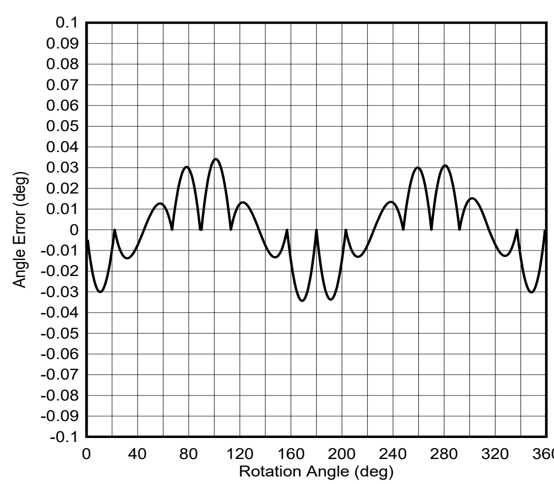

Figure 6-3. 16-point Linearization

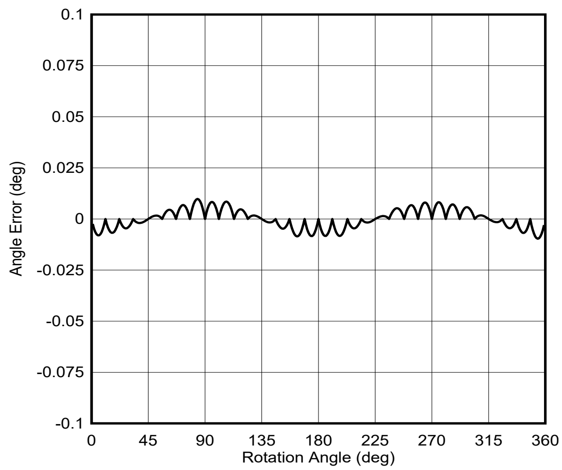

Figure 6-4. 32-point Linearization

This method requires a look-up table which is then used to approximate the error between the nearest data point using an assumption that the error varies linearly between these known values.

The other method attempts to approximate the error for all positions through an equation based solution. Since the error is cyclical in nature, it is possible to make an approximation using the sum of the combination of a sine and cosine value of each harmonic. This similarly will improve in accuracy as the number of data points increases. Using the same error profile from Figure 6-5, it is possible to reach a higher accuracy result after correcting the first 4 harmonics.

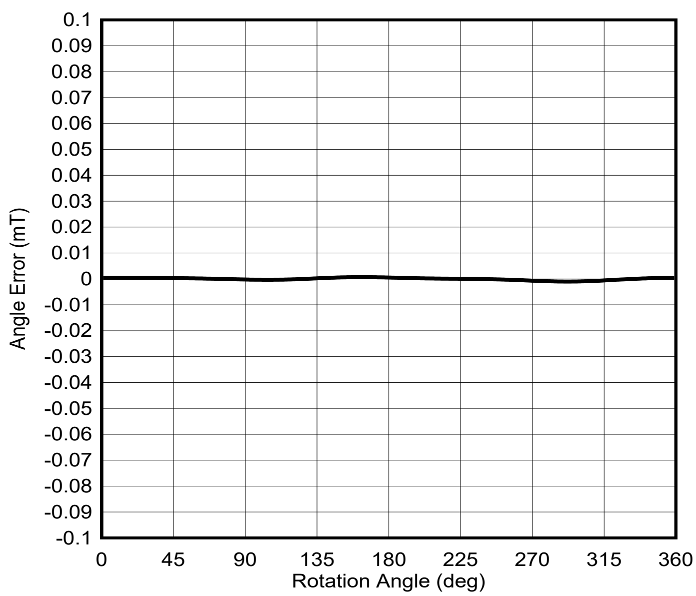

Figure 6-5. Harmonic Approximation Linearization

For more details regarding angle encoding using TMAG5170, and calibration examples captured in a lab environment, please review *Absolute Angle Encoder Reference Design with Hall-Effect Sensors for Precise Motor Position Control*.