Application Note

Reducing Quadrature Error for Incremental Rotary Encoding Using 2D Hall-Effect Sensors

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ABSTRACT

Incremental rotary encoding is an application commonly associated with latching Hall Sensors. Measurements of angular position, speed, and direction provide critical system feedback. Typically this application requires two sensors 90° out of phase from each other to achieve the desired quadrature output. Accuracy of the solution will depend on alignment and accuracy of the Hall Sensors. Devices such as TMAG5110 or TMAG5111 offer an additional in-plane sensor integrated into the package. This additional sensor is oriented in a second axis as well. This allows for intrinsic phase alignment in a single package, minimizes the layout effort by allowing a designer to use a single device, and provides excellent sensitivity threshold matching for superior performance. This application report discusses the nature of magnetic fields and design considerations related to two-dimensional Hall Sensors.

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1 Introduction

Quadrature detection of rotating magnetic fields is normally achieved using a dipole magnet by spacing two Hall-effect magnetic sensors 90° apart adjacent to the magnet. When using multi-pole magnets, this spacing may be set to any integer + ½ number of the pole spacing interval. Typically these magnets are polarized radially outward from the center of the ring, but there are also options to orient the polarization axially (vertically in the z-direction).

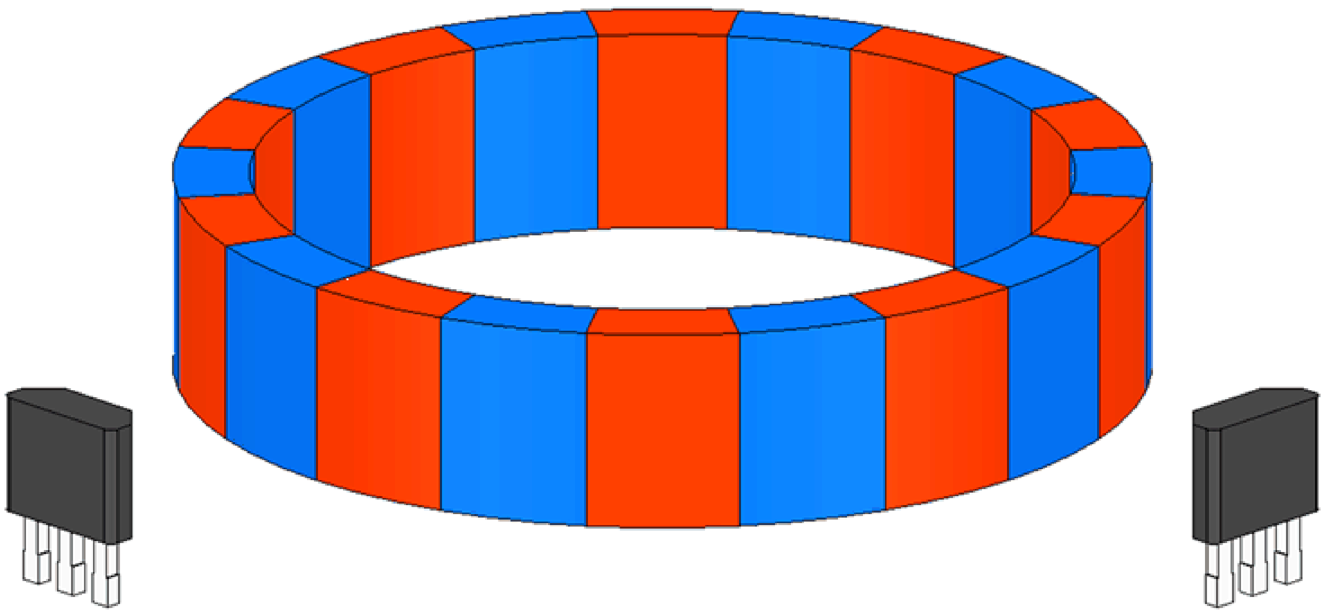

Figure 1-1. Quadrature Placement for Two Sensors

Quadrature detection in rotary encoders allows the user to monitor speed and direction of rotation as well as incremental changes in angle. Multi-pole magnets improve resolution of these angle measurements. As the number of poles increases we can resolve smaller changes in angle.

There are a few challenges that must be overcome to develop a robust quadrature solution. Here the design requires the placement of each sensor such that each detects the exact same portion of the magnetic field as the magnet rotates. Placement and alignment errors, magnet tilt, and off axis magnet rotation may all contribute to measurement error. A detailed description of these factors is available in *Using Hall Effect Position Sensors for Rotary Encoding Applications*.

Additionally, variations in device sensitivity will impact overall quadrature accuracy. For instance, let us consider a device with a typical B_{OP} point of 4 mT with ±3 mT of tolerance. We must suppose the worst case where one sensor might trigger at 1 mT and the other will trigger at 7 mT. With each sensor in plane to a 20-pole Neobond12M magnet and each perfectly placed at a distance of 3.25 mm, we monitor a magnetic flux density plot as shown in *Figure 1-2*. The magnet has an outer diameter of 25.5 mm and an inner diameter of 21.5 mm. Unless otherwise noted, we will use this magnet throughout this discussion.

The magnetic flux density observed by each sensor is identical, but is electrically out of phase by 90° due to placement. With 20-pole magnet, each pole pair occupies 36° and will define one full period at the input. Therefore, 90° electrical phase separation is equivalent to 9° of mechanical rotation. The field component in the direction radially outward from the edge of the magnet reaches a peak amplitude of just over 8 mT, which is sufficient to always tigger both devices. If we consider the unlikely scenario of the worst-case device sensitivities, there is a possibility for a maximum 4.9° of mechanical error due to sensitivity mismatch. This error results from the mismatch between the expected phase offset and the observed phase produced when the extreme BOP thresholds occur in the same system.

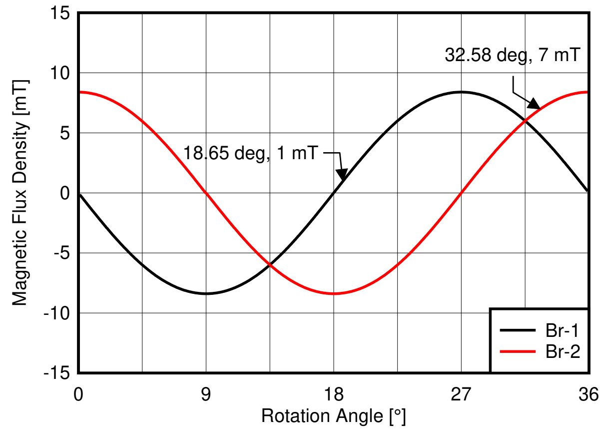

Figure 1-2. Two-Sensor Quadrature

These errors are of significant concern when trying to resolve precise angles of rotation. During continuous rotation, small quadrature errors for speed calculations may average out over time, but detecting distinct pole transitions for absolute position requires finer precision.

Using a 2D sensor such as TMAG5110 or TMAG5111 can help simplify the design and reduce build constraints. Placing both sensors internal to a single package immediately helps reduce potential alignment offsets. Additionally, the accuracy of TMAG5110 sensor is also improved. TMAG5110 combines two sensors oriented orthogonally to each other into a single package with an operating point symmetry of 1.5 mT.

We should now consider both the field directed in the z-direction and the field directed tangential (θ) to the face of the magnet.

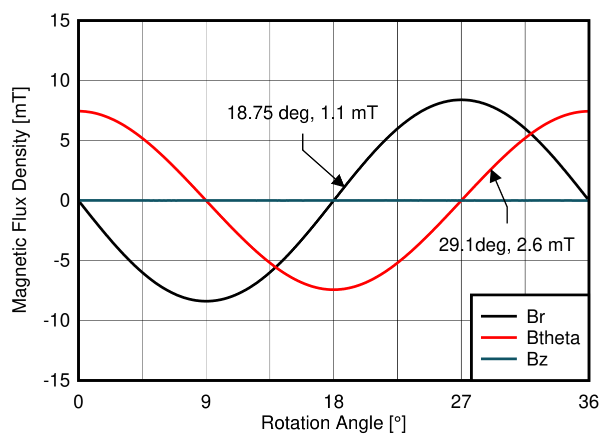

Figure 1-3. B-Field Components

In *Figure 1-3*, the 2D sensor is in the same relative position as before. We can see that the Z-component at this location is zero, so this requires a device sensitive to XY field components (B_r and B_θ). With TMAG5110 or TMAG5111 , a through-hole package type is not required to achieve this alignment as XY, ZY, and ZX options are all available in the surface mount packaging.

Here, the tangential component (B_θ) has nearly the same amplitude as the radial component (B_r). There is a slight variation in amplitude which will be additive to the error resulting from variation in device sensitivity. A 9° phase difference is expected between the two fields for this magnet. By adding the maximum B_{OP} error between sensors, the resulting error is about 1.35°. This is a significant improvement on the previous scenario.

While this improvement is good, it could be improved further by carefully considering the nature of the magnetic field of a magnet and how it relates to our sensor placement.

2 Latch Response of the 2D Hall Effect

First consider the output response of the 2D latch with respect to the input magnetic flux density.

TMAG5110 and TMAG5111 each have two integrated latches that update their results into OUT1 and OUT2. Each of these outputs will then have a latch functionality. *Figure 2-1* shows the response to different magnetic poles for each of the outputs. The TMAG5111 outputs are not directly connected to the two integrated latches. Additional calculations have been added to output the speed and direction instead.

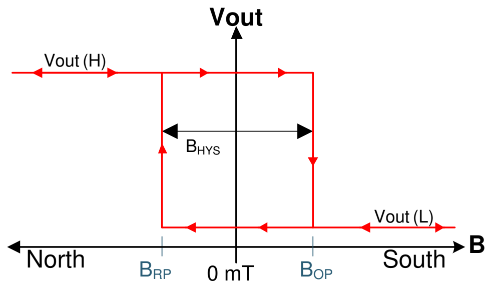

Figure 2-1. Latch Functionality

Figure 2-2 shows the magnetic response of TMAG5110 and TMAG5111 to a sinusoidal field. The sinusoidal curves represent the observed magnetic field produced by the rotating magnet.

The TMAG5110 response shows both outputs reacting to this signal by going low once the field exceeds B_{OP}, and likewise each output goes high only when the field component crosses B_{RP} in the opposing direction.

The TMAG5111 response shows how those two signals are used to create both speed and direction as outputs.

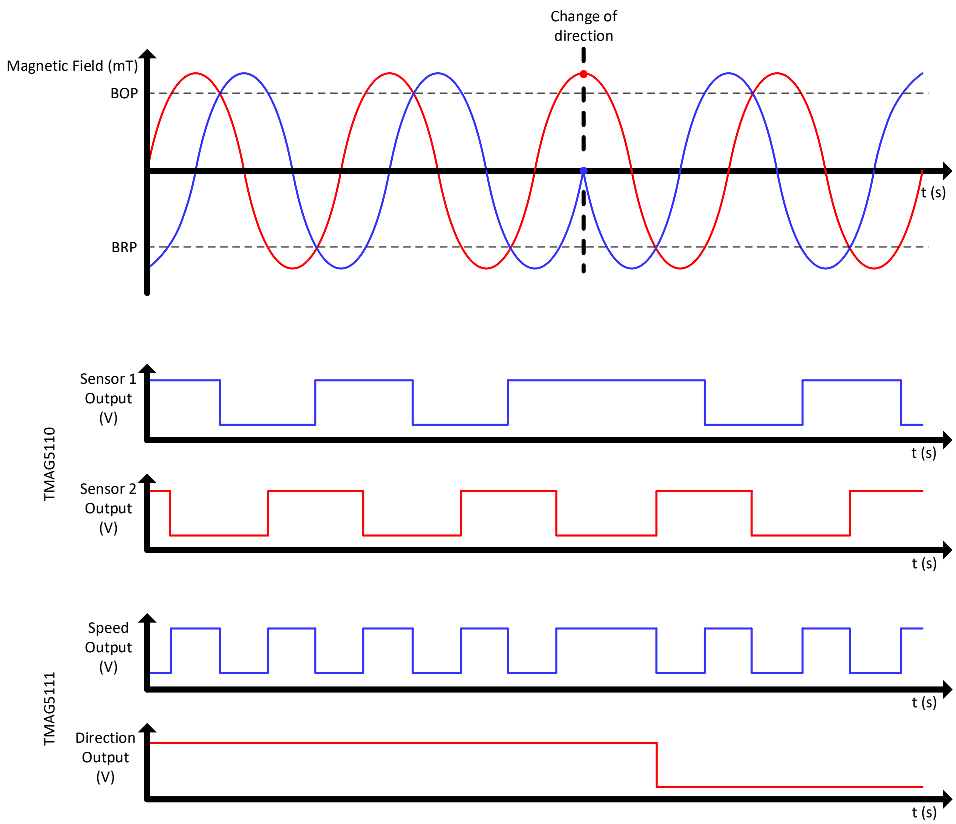

Figure 2-2. Output Behavior

3 Two Axis Sensor Consideration

Several factors impact the expected results when using a multi-axis Hall Sensor. These include magnet selection, sensor options, and physical placement and alignment. Each of these should be considered to achieve the best quadrature results.

3.1 Magnet Selection

Selecting the best magnet for any given application will vary based on design constraints such as available space, required orientation, and cost. Typically stronger materials, larger magnet sizes, and custom shapes or configurations will all add to the cost of the magnet.

3.1.1 Pole Count

Pole count of the magnet will impact the minimum resolution of angular measurements. For instance, in a basic cylinder magnet with diametric polarization only two discrete positions for each sensor can be determined. Because of the phase differences, we can determine angular position to 90°. As the pole count of the magnet increases our angular step size improves. This change in resolution will also help scale the expected angle error that results from amplitude or sensitivity mismatch.

There is a trade off when increasing pole count. Magnetic flux density, or B-Field, in each direction will weaken as the pole count increases. Therefore, a given sensor needs to be closer to the magnet or have greater sensitivity to detect each pole transition. Figure 3-2 to Figure 3-4 illustrate the simulation results of the B-Field produced by a magnetic ring with 10 poles and another with 20 poles. Here the sensor is no longer in plane with the magnet, but has been displaced downward 1.5 mm beneath the outer edge. We observe in this location that B_Z is the dominant component of the B-Field vector with a peak value of about 10 mT in the 20 pole case.

In the simulation examples, it is informative to use cylindrical coordinates rather than Cartesian. As a result, instead of representing the output vectors in terms of X, Y, and Z, the plots have coordinates relative to R (directed radially outward from the z-axis), θ (directed tangentially with respect to a point at radius R), and Z. This ensures that no matter where the sensor is placed with respect to the magnet that we can correctly extract the appropriate vectors as we explore the space surrounding the magnet.

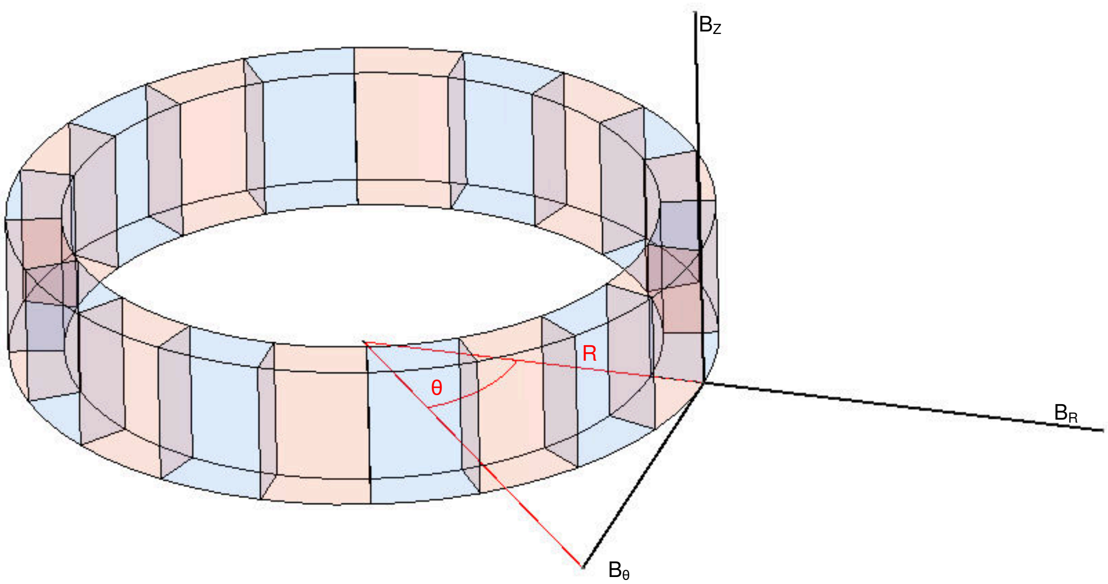

Figure 3-1. Cylindrical Coordinate System

Each magnet shares identical dimensions, material properties, and sensor placement. The only difference is the number of poles. Notice the drop in measurable magnetic field as a result of increasing the number of poles. Also, notice that the sinusoidal shape present in the θ component of the 20-pole version becomes more triangular for the 10 pole magnet. A more sinusoidal response is expected here with a larger air gap, but this comes at the cost of reduced amplitude.

A higher pole count magnet provides better angular resolution, but also results in a weaker magnetic field. The measured magnetic flux density must be large enough in both measured axes to properly detect quadrature.

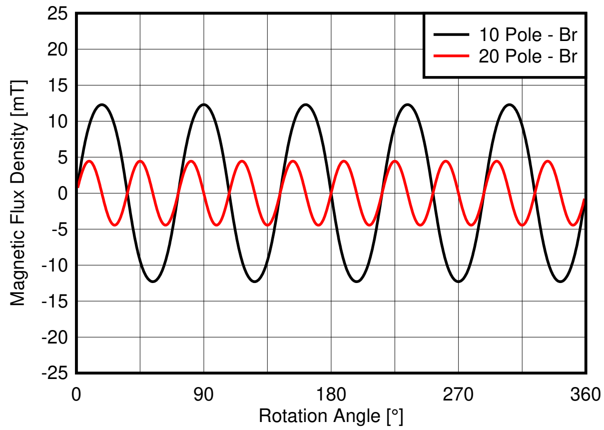

Figure 3-2. Impact of Pole Count - B_r

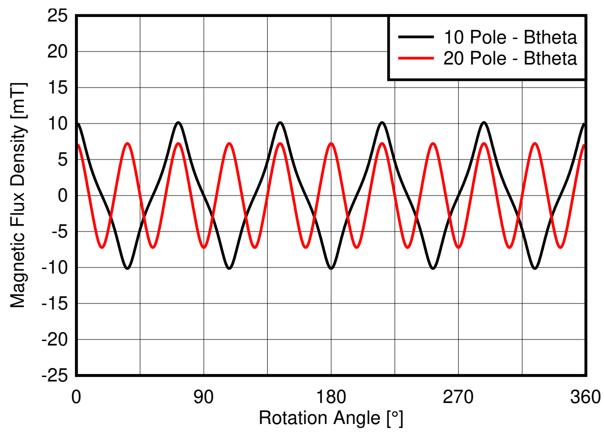

Figure 3-3. Impact of Pole Count - B_θ

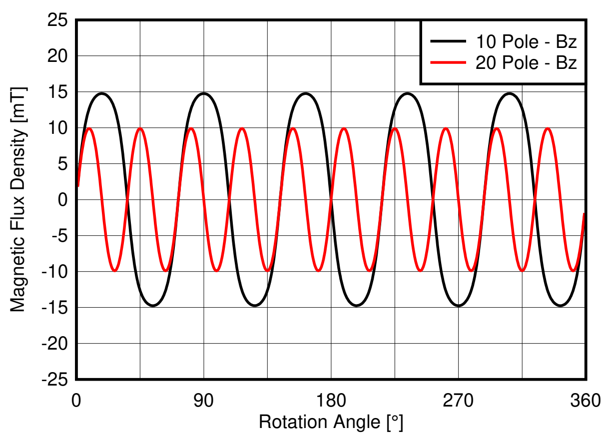

Figure 3-4. Impact of Pole Count - B_z

3.1.2 Magnet Strength

If constrained by placement and required resolution, it may be necessary to use a magnet material with stronger magnetization. In a similar fashion, we can compare the result of our bonded ceramic type magnet with that of N35 and SmCo18 type magnets. The placement beneath the outer edge of the magnet is used again, and only the material type is varied. Notice that the Neodymium type magnet offers a much greater peak amplitude than the molded ceramic magnet with an identical pole count.

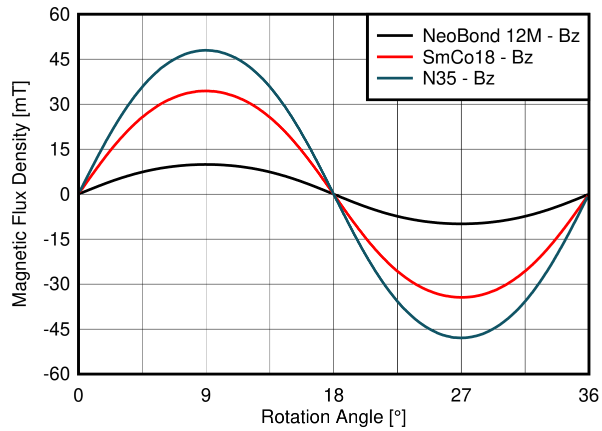

Figure 3-5. Variation of Magnetic Material

By extension this shows that using a stronger magnet material will allow the sensor to detect quadrature at greater distances as the magnetic flux density decreases as a function of distance.

3.2 Sensor Selection

Choosing the correct sensor variation for the application can also impact results. Specifically, sensitivity thresholds and axes of sensitivity are device options that will govern performance.

3.2.1 Axes of Sensitivity

TMAG5110 and TMAG5111 each offer all possible combinations of two axes. That is XY, ZY, and ZX. Each combination is available as a different package variant within the same product family. The polarity which is best for a given application will vary based on how the sensor is to be aligned with the magnet. These devices offer flexibility to use a surface mount package without the need for additional PCBs or devices that require significant vertical space. The following sections show some possible configurations.

3.2.1.1 In-Plane Sensor Alignment

The outer edge of the magnet is the area where the magnetic field is the strongest. Placing the sensor on the outer edge of the magnet then allows the most flexibility in air gap and sensitivity selection. The following different figures show how to use the different versions of TMAG5110 and TMAG5111 with the magnet placed adjacent to the outer edge (In-Plane).

Option A - X and Y axes sensitivity enables the sensor to be positioned in the same plane as the ring magnet. The sensor can be positioned facing the magnet or also looking at the magnet from the side. The device can also be turned at 180° along the Z axis.

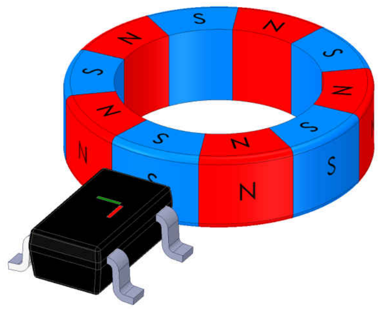

Figure 3-6. XY Outer Edge 1

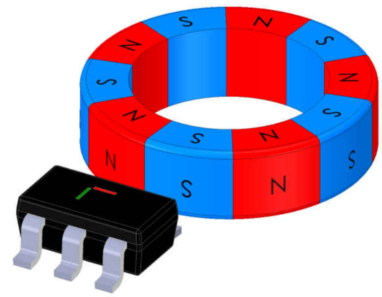

Figure 3-7. XY Outer Edge 2

Option B - Z and X axes enable the sensor to be positioned at the top of the package, facing the ring magnet or the front side of the device facing the magnet. The device can also be turned at 180° along the Z axis.

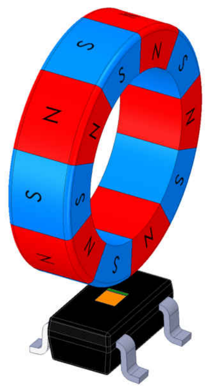

Figure 3-8. ZX Outer Edge 1

Figure 3-9. ZX Outer Edge 2

Option C - Z and Y axes enable the sensor to be positioned at the top of the package, facing the ring magnet or the side of the device facing the magnet. The device can also be turned at 180° along the Z axis.

Figure 3-10. ZY Outer Edge 1

Figure 3-11. ZY Outer Edge 1

3.2.1.2 Out-Of Plane Sensor Alignment

With the sensor placed outside of the plane of the magnet ring, there will be a reduction to the observed amplitudes for each component of the B-Field when using an fixed air gap. As a result, there is reduced flexibility for the distance between the sensor and magnet. High sensitivity devices (or devices with a low B_{OP} threshold) allow the application to continue to detect pole transitions even when the device is placed beneath the outer edge. This is particularly helpful in situations where space is limited and the sensor must fit within the magnet diameter.

Option A - X and Y axes enable the sensor to be positioned facing the side edge of the magnet. It can also be placed with the side edge of the sensor facing the side of the magnet. The device can also be turned at 180° along the Z axis.

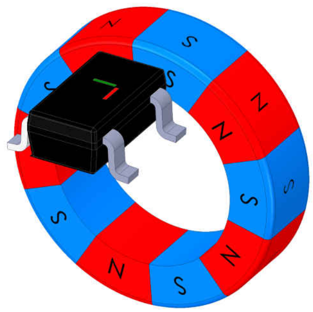

Figure 3-12. XY Side Edge 1

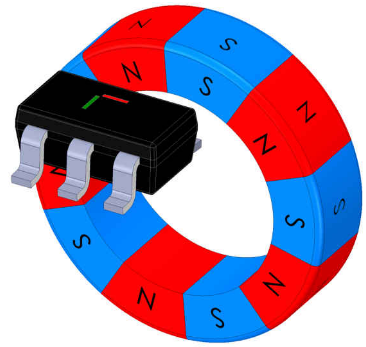

Figure 3-13. XY Side Edge 2

Option B - Z and X axes enable the sensor to be positioned facing the side edge of the magnet or the top of the package facing the side edge of the magnet. The device can also be turned at 180° along the Z axis.

Figure 3-14. ZX Side Edge 1

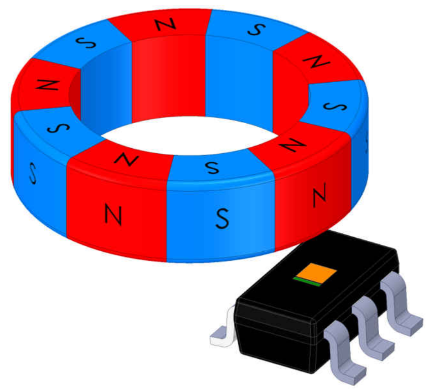

Figure 3-15. ZX Side Edge 2

Option C - Z and Y axes enable the sensor to be positioned facing the side edge of the magnet or the top of the package facing the side edge of the magnet. The device can also be turned at 180° along the Z axis.

Figure 3-16. ZY Side Edge 1

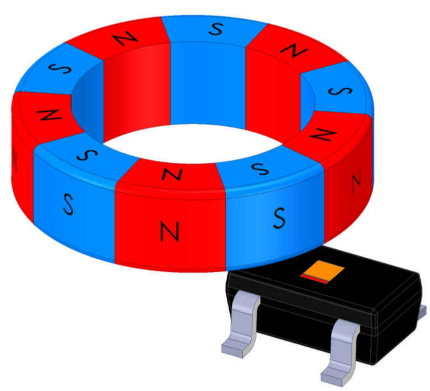

Figure 3-17. ZY Side Edge 1

3.2.2 Sensor Placement

To provide further insight regarding the magnetic field produced by the magnet we will examine the expected variations now by showing the expected response at each of the primary locations. Specifically, we will show centered along the axis of rotation (On-Axis), along the outer edge (In-Plane), and to the Side (Out-of-Plane).

Optimization for each location is possible, and the steps taken to improve overall results will be discussed.

3.2.2.1 On-Axis Magnetic Field

Unlike all of the other scenarios shown in this document, an On-Axis measurement is best suited when using a diametric magnet with only a single pole pair. The sensor should be placed beneath the magnet along the axis of rotation for this type of alignment.

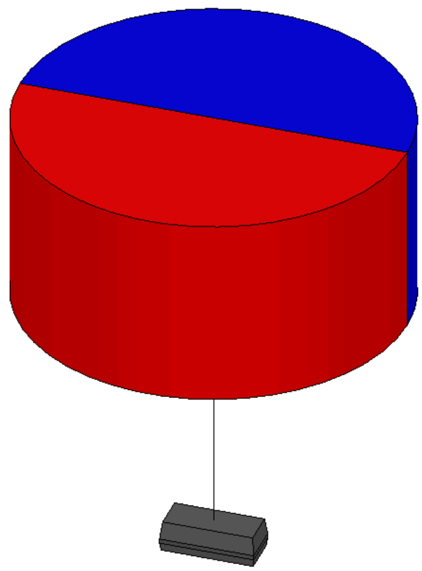

Figure 3-18. On Axis Alignment

In this position, the magnetic field will always be directed parallel to the magnet face as it rotates, and will therefore produce no z-component.

For this example, we will deviate from the 20-pole bonded ceramic magnet and show the response from a 24.5-mm diameter disc magnet with a thickness of 12.25 mm. The sensor is placed approximately 10 mm below the magnet. Notice that the magnetic flux density for each component has a peak of 75 mT. It would certainly be possible for TMAG5110 or TMAG5111 to operate in this system with a smaller magnet or at a further distance.

What is noteworthy here is that the two components are perfectly 90° out of phase, and share the same peak amplitude. Alignment for this case is fairly simple, with a minimal impact due to amplitude differences.

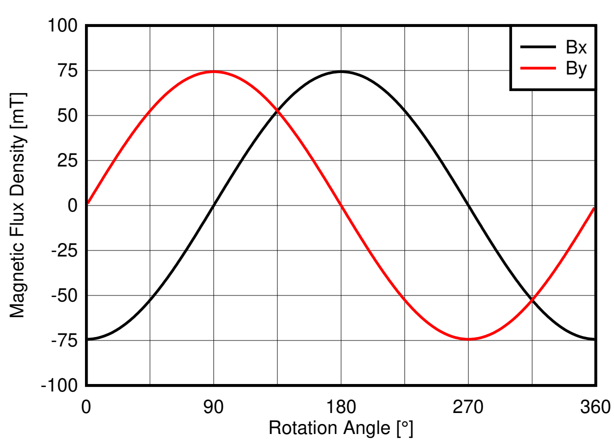

Figure 3-19. On-Axis Magnetic Field Components

The drawback for this type of magnet and alignment is resolution. We can only determine each 90° step. To get finer resolution with this type of magnet, the magnet needs to be geared to rotate at a higher ratio than the main body being sensed.

While we would only observe quadrature error to result from sensitivity mismatch, we still expect as much as 1.16° error with the worst case matching. Despite the input having a significantly larger magnitude than in the multi-pole case, the error is still greater than 1° due to the mechanical and electrical phase having a 1:1 ratio. When using a multi-pole magnet the angular resolution improves and will scale the error down.

3.2.2.2 In-Plane Magnetic Field

Figure 3-20 shows in-plane placement. Instead of using two separate devices to detect quadrature, we have a single 2D sensor coplanar to the magnet.

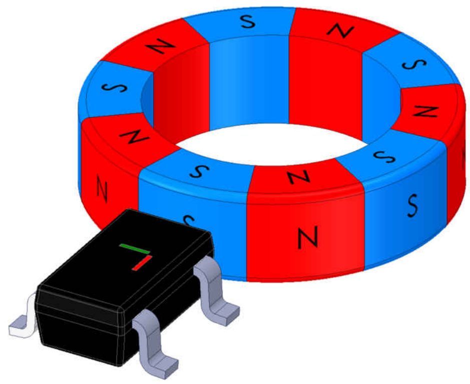

Figure 3-20. Sensor In-Plane

The radial component of the magnetic field is about the same amplitude here as it was beneath the magnet with a smaller air gap. When placed with a 3.25 mm spacing between the sensor and the magnet face we notice that the peak amplitudes between the two relevant components are quite similar, and there is no z-component.

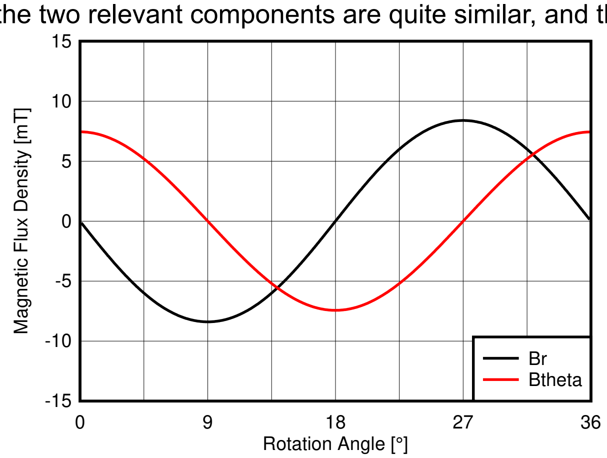

Figure 3-21. In-Plane Magnetic Field Components

In this alignment it is possible to achieve greater distances from the magnet. However, many systems may be mechanically prohibitive to using this approach. As shown in the *Introduction*, we can expect about 1.35° error due to amplitude mismatch and sensitivity error combined. If the magnet were placed closer to the sensor, this error would be expected to decrease.

3.2.2.3 Out-of-Plane Magnetic Field

Out-of-Plane placement can be the easiest to configure mechanically. There are also measurable magnetic field components in all three directions. This gives the greatest flexibility for tracking magnet rotation.

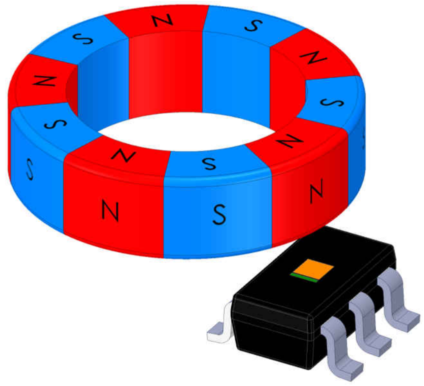

Figure 3-22. Sensor Out-of-Plane

There is a significant issue here. The peak amplitudes of each component are so different from each other that there will be noticeable error. If we consider the components which are closest matched, Z and θ, an worst case error of about 1.83° is expected. This error becomes more significant with the sensor placed further from the magnet where the field is weaker.

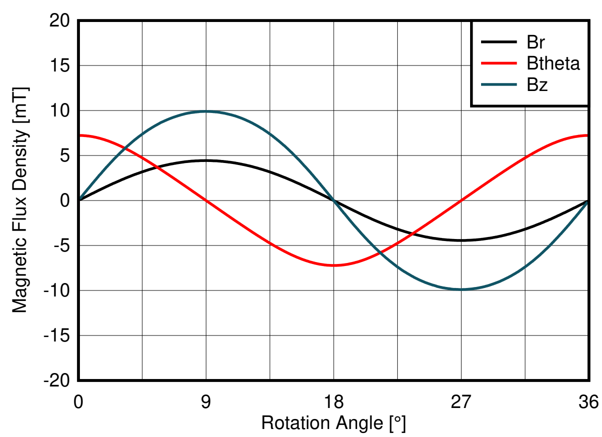

Figure 3-23. Out-of-Plane Magnetic Field Components

With placement of the sensor out-of-plane, an additional option exists for magnet selection. While not as common, it is also possible to obtain multi-pole ring magnets with axial polarization, or in the z-direction.

For comparison, observe the change to the peak amplitudes available with this type of magnet. In this case, the same material and dimensions are used, but the polarization is now directed outward from the face of the magnet. This type of polarization will allow for greater air gaps and pole counts for sensors in the out-of-plane alignment. However, they fail to produce adequate inputs when the device is in-plane with the magnet. These are often manufactured as custom magnets, and tend to be less commercially available .

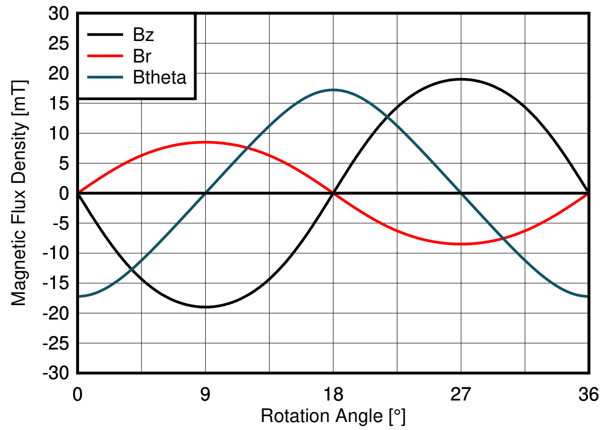

Figure 3-24. Face Polarized Magnet

3.2.3 Sensitivity Selection

Hall Effect sensors are typically offered at multiple sensitivity levels. Since magnetic field components tend to have unequal amplitudes, it is typically best to select a threshold as close to the zero cross point to achieve the best quadrature alignment. At the zero cross point, field vector components will still be aligned 90° out of phase regardless of amplitude mismatch.

Based on this, typically the lower threshold option would provide the best performance. What must be considered, however, is whether or not stray external magnetic fields may also be present. In some applications, it is not uncommon to observe small magnitude fields from other sources. In this case, it may be advantageous to select a sensitivity option with a higher maximum B_{OP} threshold to provide better immunity to these sources while still maintaining a relatively low trigger point.

4 Optimizing for Accuracy

Now that we have a complete picture of what to expect from a given magnet and sensor, it is possible to consider options to optimize quadrature alignment. This is most easily done by either changing the selected magnet or by finding an ideal placement to improve matching between the sensed magnetic flux density components.

4.1 Optimizing Placement for Accuracy

From our findings based on sensor placement we can deduce a method to minimize the error that results from mismatch in each field component. Consider Figure 4-1 which shows a side view of the 20-pole ring magnet we have been analyzing.

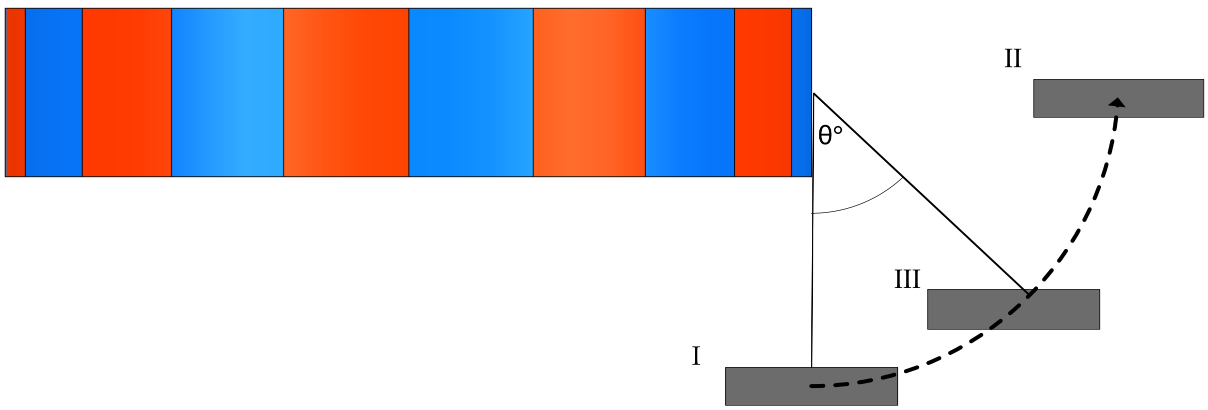

Figure 4-1. Finding Optimal Placement

We have already closely examined positions I and II. In position I (out-of-plane), the z-component is the strongest field component, and in position II (in-plane) the z-component is zero. It is reasonable to expect that as there is a position III at some angle of rotation outward where the z-component will equalize with one of the other two field components. Likewise, the radial component has the largest magnitude in position II, where is it the smallest component in position I.

A simulation sweep to find a possible position III resulted with an angle of 38.9°. Matching between B_r and B_θ was achieved at this angle when using a fixed range of 3.25 mm to the center of the face of the magnet. Magnetic field components can be seen in Figure 4-2.

The resulting B_r and B_θ fields have a peak amplitude of 12.4 mT, and the resulting worst case angular error of 0.85° will be entirely due to sensitivity mismatch.

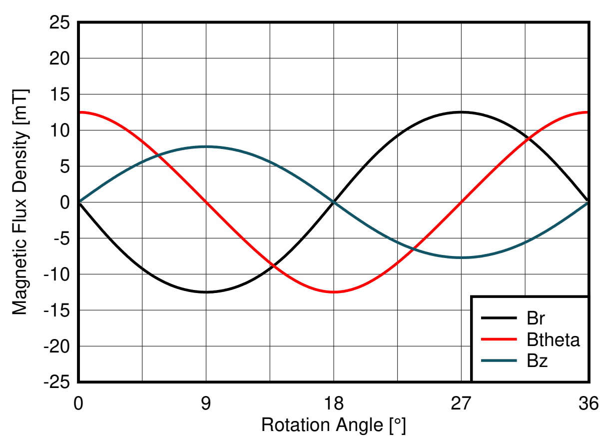

Figure 4-2. Bz and Bθ Matched

While position I and II are common and easily implemented, position III can be difficult to achieve in practice. It does, however, provide optimal input matching for the best overall performance.

As an alternative to finding the ideal placement of the sensor, it will also be beneficial to consider how to modify the magnet to improve performance as well.

4.2 Optimizing a Magnet for Accuracy

An additional alternative to reduce error is to increase the magnet strength. With amplitude mismatch, we can expect the greatest errors to arise when the B_{OP} & B_{RP} thresholds are close to the peak input value. Moreover, the zero crossings always remain electrically out of phase by 90°. Therefore, the closer the B_{RP} & B_{OP} thresholds are relative to the zero crossing value, the better the quadrature result.

See Table 4-1 extracted from the material variation simulation. To find angle error we will find where the z-component of the magnetic field reaches 1.1 mT and the θ component reaches 2.6 mT. This is to ensure we capture the maximum sensitivity error possible.

Table 4-1. Impact of Magnet Strength on Quadrature Error

Material	B_{OP} - Z	B_{OP} - θ	Angle Error
Bonded Ceramic	0.57°	29.4°	1.83°
SmCo 18	0.15°	27.68°	0.53°
N35	0.12°	27.49°	0.37°

5 Application Implementation

For demonstration, the TMAG5110 sensor with the high-sensitivity option for B_{OP} threshold oriented in the ZX axes was selected to use alongside a 20-pole NeoBond magnet. Each pole therefore occupies 18° of one complete revolution. The magnet was rotated 108° to capture 6 complete pole transition cycles. The expectation when analyzing the output will be that there is a 9° separation between the two outputs.

To start, the sensor was placed centered directly beneath the outer edge of the magnet. The sensor was then stepped radially outward (in the x-direction) from the edge of the magnet in 0.635 mm steps (0.25 mil) to demonstrate the shift in quadrature accuracy and find the ideal air gap with a fixed spacing in the z-direction. This approach was a simpler way to vary the angle in laboratory experimentation as adjustments to a single axis were more practical.

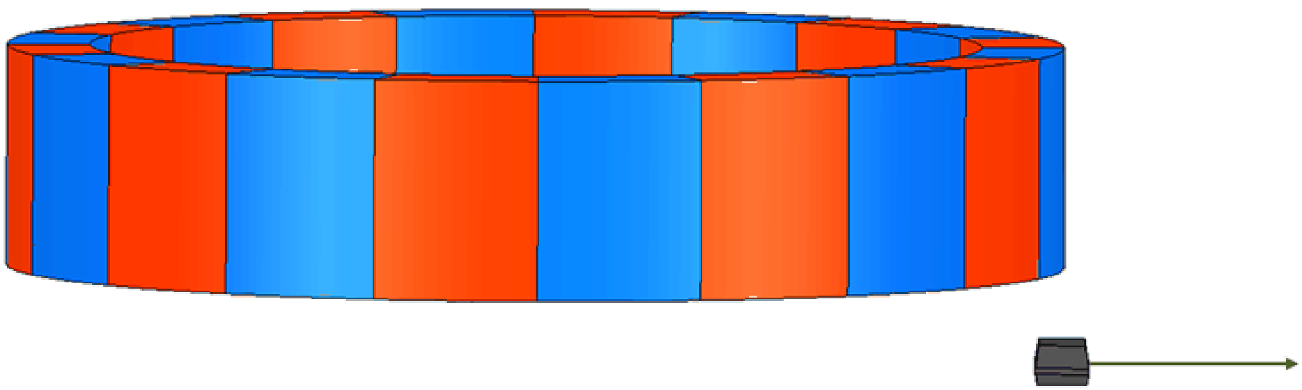

Figure 5-1. Laboratory Measurement Setup

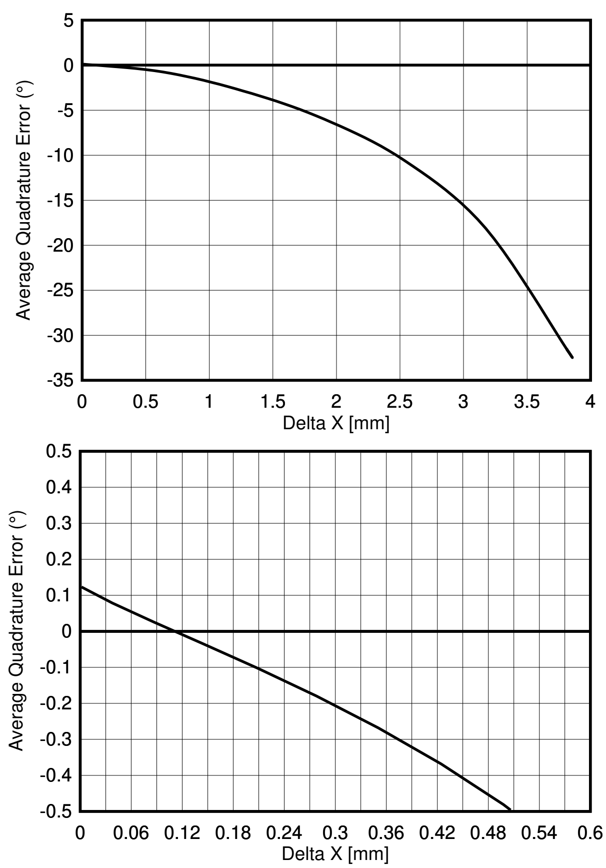

Figure 5-2. Average Quadrature Error vs Placement

Notice that the quadrature error observed was near its minimum at the start position, but was improved by moving the sensor outward. The results captured show the best location for this setup was approximately 0.11 mm away from the outer face of the magnet. Beyond 3.85 mm, the outputs could no longer properly detect the pole transitions.

In practice, gathering empirical data is a useful alternative to simulation data, and provides a powerful means to confirm simulated expectations. It is important to note that several non-ideal factors are present with this method and help realize the impact of system tolerances on the overall result.

Magnet tilt and wobble, if large enough, will produce shifts in quadrature alignment. One pole transition might occupy 18.2°, while another occupies only 17.8°. Additionally, if the sensor is not completely orthogonal to the B-Field then the sensor might pick up more or less input than anticipated. Another consideration is that each device will demonstrate variations in the exact B_{OP} / B_{RP} thresholds. These threshold shifts will result in small variations in quadrature accuracy.

6 Summary

Two dimensional hall effect latches, such as TMAG5110 and TMAG5111, offer a practical means to measure quadrature for incremental rotary encoding applications. These devices allow the user to select which axes of sensitivity are most ideal and can then be placed On-Axis, In-Plane, or Out-of-Plane. Matching device sensitivity and phase alignment, which are common sources of error when using discrete sensors, requires very little effort due to the excellent matching and multiple axes of sensitivity available by integrating two orthogonal sensors into a single package.

The performance in these applications can be improved even further by understanding the magnetic field and how it relates to the quadrature results of a two-dimension dual Hall-effect latch. By carefully examining placement and magnet selection, it is possible to minimize the total measurement error. Having this understanding leads to an effective method for improving quadrature alignment and accuracy.

Once an alignment has been selected, it is recommended to adjust the position of the sensor along a single axis until quadrature error is minimized in a test configuration. For testing with a sensor integrated into an existing application, consider the *Hall Adapter EVM* which provides a miniature PCB for this purpose. If placement variation is constrained, then increasing pole count or magnet strength can also provide an alternative to minimize the total measurement error of the system.

7 References

- Texas Instruments, *TMAG5110*
- Texas Instruments, *TMAG5111*
- Texas Instruments, TI E2E™ Hall-Effect Sensor Forum
- Texas Instruments, *Hall-Effect Latches and Switches Portfolio*
- Texas Instruments, *Using Hall Effect Position Sensors for Rotary Encoding Applications*

8 Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision A (January 2021) to Revision B (October 2021)	Page
• Updated the title for search-engine optimization	1

Changes from Revision * (October 2020) to Revision A (January 2021)	Page
• Text and plots updated to reflect final specifications of TMAG5110 at time of release	1