AZD127 – Hall-Effect Rotation Sensing Design Application Note

Design Guidelines for On- and Off-axis Hall-effect Rotation Applications

Contents

1 Introduction 2

2 Hall-Effect Sensing Principle 2
2.1 Measurement Principle . . . 2
2.2 Magnet Orientation . . . 3
2.3 Application Examples . . . 3

3 General Design Parameters and Concepts 4
3.1 Main Design Parameters . . . 4
3.2 Linearity . . . 4
3.3 Phase Angle and Jitter . . . 6
3.4 Magnet Material . . . 6
3.5 Magnet Grading . . . 7

4 On-Axis Hall-Effect Sensor Design Guide 8
4.1 IC Selection . . . 8
4.2 Magnet Positioning . . . 8
4.2.1 Magnet Height h . . . 8
4.2.2 Magnet Lateral Offset . . . 9
4.2.3 Magnet Wobble . . . 10
4.3 Magnet Outer Diameter d_o . . . 12
4.4 Magnet Width w . . . 12
4.5 Design Summary . . . 13

5 Off-Axis Hall Sensor Design Guide 14
5.1 IC Selection . . . 14
5.2 Axis-parallel Configuration . . . 14
5.2.1 Magnet Positioning . . . 14
5.2.2 Magnet Height h . . . 14
5.2.3 Phase Angle and Jitter . . . 15
5.2.4 Magnet Lateral Offset . . . 15
5.2.5 Magnet Wobble . . . 15
5.2.6 Magnet Inner Diameter d_i and Outer Diameter d_o . . . 16
5.2.7 Magnet Width w . . . 16
5.2.8 Configuration Guide . . . 16
5.2.9 Design Summary . . . 17
5.3 Axis-perpendicular Configuration . . . 18

6 Conclusion 19

1 Introduction

Azoteq offers ICs that function as Hall-effect rotation encoders, which measure the absolute angle of a nearby magnet. This is achieved by using up to four integrated hall plates that measure variations in the magnetic field generated by a diametrically-polarised disc or ring magnet. This document aims to provide general design guidelines and a best-practice approach to implementing rotation sensing using Hall-effect technology.

2 Hall-Effect Sensing Principle

2.1 Measurement Principle

The Hall-effect measurement principle involves the use of a magnetic field to induce a potential, known as the Hall-effect voltage, in the measurement circuitry. The magnetic field itself must be external to the circuitry and may be created using either a permanent magnet (ferromagnetic material) or an electromagnet. The Hall-effect voltage will change depending on the strength of the magnetic field. This principle is illustrated in Figure 2.1, which shows the magnet as well as the measurement circuitry, which will be referred to as the sensor [1].

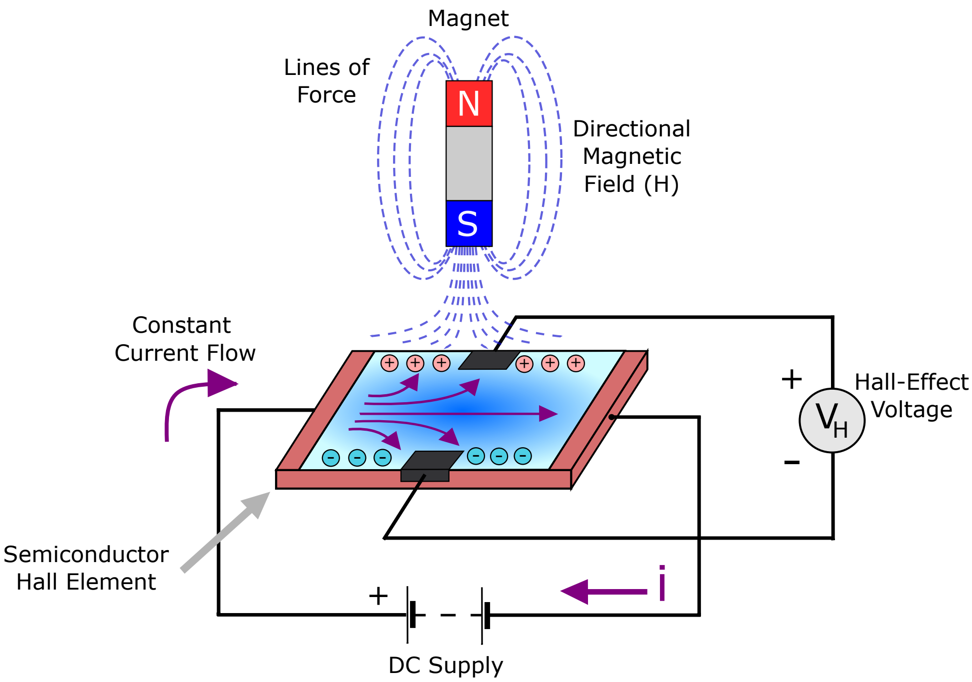


Figure 2.1: Illustration of Hall-Effect Measurement Principle (adapted from [1])

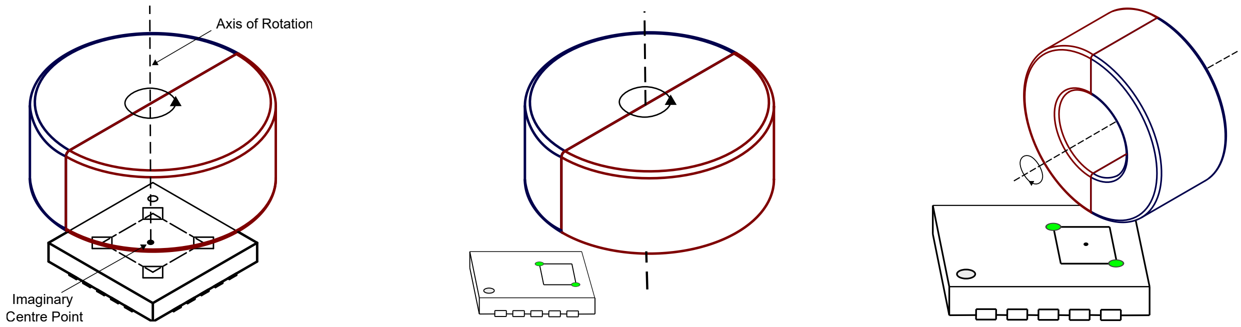
The sensor consists of a semiconductor Hall-effect element (or Hall-effect plate), with a constant electrical current flowing through the plate as well as a voltage measurement made on the sides of the plate parallel to the current flow direction. When a magnet is introduced near the plate, its magnetic flux will exert a force on the plate, forcing some of the charge carriers to relocate to the side of the plate, which in turn creates a measurable net potential (or Hall-effect voltage). Should the magnet move closer to the sensor, more charge carriers will be forced to the side due to increased magnetic flux, leading to a higher Hall-effect voltage. The reverse is true when the magnet moves further away from the sensor. Thus, the Hall-effect voltage is a function of magnetic flux density and may be exploited to sense changes in a magnet's position, motion, or rotation. Given the horizontal orientation of the Hall-effect plates on the ICs' die, only the *vertical* or *z*-component of the magnetic field is measured.

The main advantage of the Hall-effect sensing approach is its contactless nature, making it a robust and maintenance-free approach. However, its performance will be limited by the selection of the magnet.

2.2 Magnet Orientation

The magnet may be oriented in two main ways, namely *on-axis* or *off-axis*, which explains the magnet's positioning relative to the Hall-effect plates of the IC. On-axis means that the magnet's axis of rotation and the imaginary centre point that exists between the Hall-effect plates are aligned. This is illustrated in Figure 2.2a. Off-axis means that there is no alignment between the magnet rotation axis and centre point of the plates.

Furthermore, the off-axis configuration may be subdivided into *axis-perpendicular* and *axis-parallel*, illustrated in Figures 2.2b and 2.2c, respectively. As the names suggest, this subdivision further explains the rotation axis's alignment, which may either be perpendicular to the Hall-effect plates or parallel to them. Finally, all magnets shown here are circular. With a focus on rotational sensing, the use of a circular-shaped magnet is appropriate.



(a) On-axis (Axis-Perpendicular) *(b) Off-Axis (Axis-Perpendicular)* *(c) Off-Axis (Axis-Parallel)*

Figure 2.2: Illustration of On- and Off-Axis Orientations Relative to the IC

The main advantages of the on-axis configuration are that no phase angle calibration is required, it features improved linearity compared to off-axis, and it is robust against magnet wobble. On the other hand, the off-axis (axis-parallel) configuration allows for a simpler mechanical assembly, but will it require phase angle calibration and it will be more prone to linearity errors.

2.3 Application Examples

Popular examples of on-axis Hall-effect rotation sensing include thermostat controllers, as well as volume control knobs. Off-axis examples include measurement wheels and revolution counters. A mouse with a scroll wheel and thumb wheel as shown in Figure 2.3b is an example where both on- and off-axis configurations are employed: the scroll wheel may use on-axis, while the thumb wheel uses an off-axis setup.

(a) On-axis Example: Volume Knob

(b) On-Axis Main Scroll Wheel, Off-Axis Thumb Wheel

Figure 2.3: Example Applications of On- and Off-axis Hall-Effect Rotation Sensing

3 General Design Parameters and Concepts

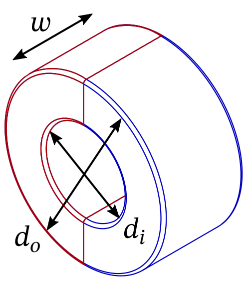
3.1 Main Design Parameters

To achieve optimal sensor performance, the following key design parameters should be considered:

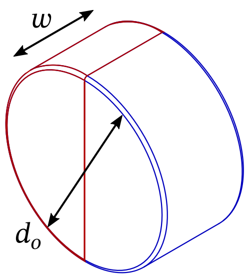
- Magnet material and grading
- d_o, the outer diameter of the magnet,
- d_i, the inner diameter of the magnet,
- w, the width or thickness of the magnet,
- h, the height of the magnet above the PCB.

Figure 3.1a and 3.1b illustrate the dimensions mentioned in the list above as applicable to ring and disc magnets, respectively. These design parameters will determine the strength of the magnet field detected by the Hall-effect plates. Sufficient field strength is necessary to ensure low noise and to minimise linearity errors. Ideally, the system should be designed such that the hall plates are exposed to magnetic field densities between 20 mT and 100 mT.

The effect of these parameters will be explored in detail in Sections 4 and 5.



(a) Ring Magnet Dimensions



(b) Disc Magnet Dimensions

Figure 3.1: Key Dimensions of Permanent Magnets

3.2 Linearity

Linearity is a measure of the maximum potential error in the angle measurement. These errors arise from inconsistent magnetic field densities at the Hall plates. For example, mechanical tolerances could cause the plates to measure different amplitudes or DC offsets. Figure 3.2 shows an example of large errors caused by mechanical misalignments. The output angle on the Y-axis is shown as an 16-bit integer scale (0 to 65535), as measured by the IC. It is clear that the IC's output deviates slightly from the expected output at some magnet angles.

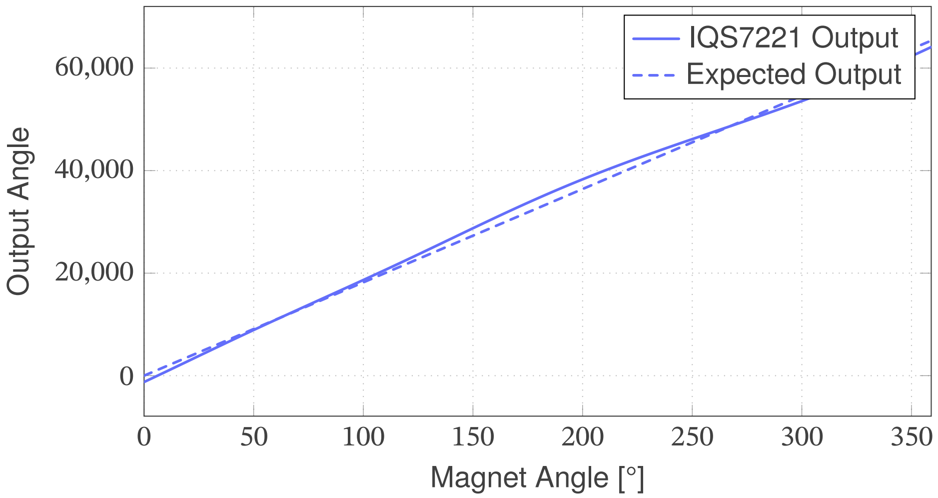


Figure 3.2: IC Angle Output vs True Angle

By subtracting the known true angle from the IQS7221's output, the linearity of the sensor can be determined, as illustrated in Figure 3.3.

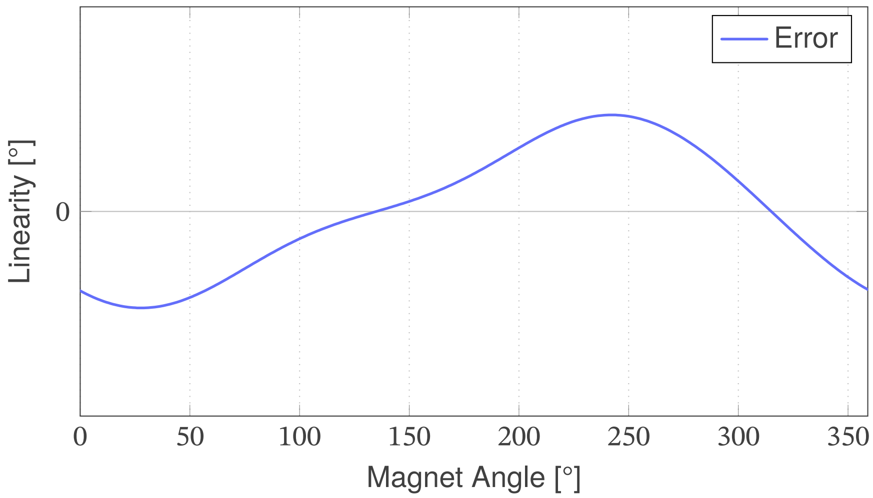


Figure 3.3: IC Angle Linearity Plot

Linearity is therefore defined as the maximum amplitude of the above error graph and is specified in ±°. For any measurement obtained from the IQS7221, the true angle is within this linearity value. A lower linearity value is desirable, as it implies a smaller potential error in the output angle.

The linearity of the sensor is a function of multiple physical factors, including:

- Misalignment of the magnet
- Wobble on the rotation axis
- Magnetisation error
- Imprecise calibration of the phase angle (for off-axis applications)

All applications will have some maximum linearity requirement. This requirement drives magnet selection and mechanical design.

3.3 Phase Angle and Jitter

As the magnet rotates, the magnetic field density at the IC's Hall plates changes. These changes are processed to produce two new signals that are out of phase from each other. The phase difference is referred to as the *phase angle*. The phase angle is dependent on the magnet's position and orientation. For on-axis applications, the phase angle is usually 90°, but for off-axis applications, this value has to be calibrated.

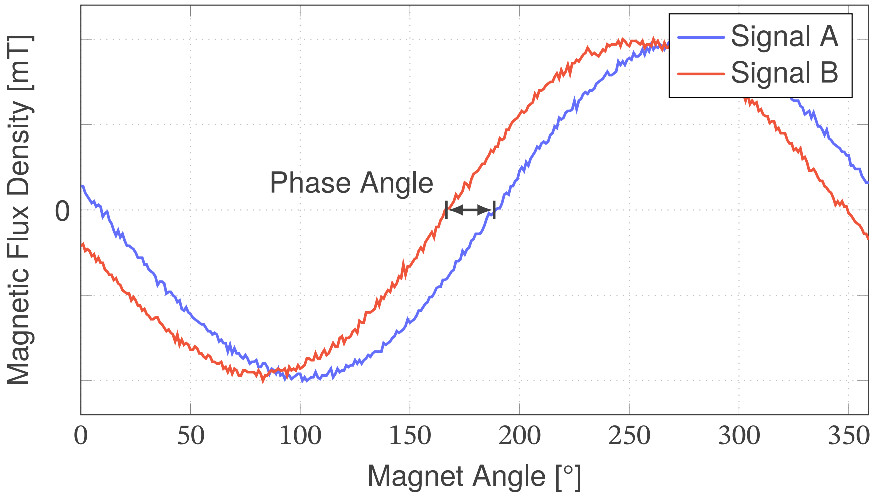


Figure 3.4: Graphs Illustrating Phase Angle and Jitter

In practice, the signals shown in Figure 3.4 will have some form of noise contamination, called *jitter*. For the off-axis case where the phase angle may be low, the IC's ability to reliably detect the rotation angle is compromised. To minimise this, the designer must maximise the phase angle as far as possible by minimising the magnet height h, and by selecting a sufficient magnet inner diameter d_i and outer diameter d_o.

3.4 Magnet Material

The choice of magnetic material will have a significant influence on the performance of the sensor. Some magnetic materials have a higher energy density than others, which allows for a smaller magnet size to be used to achieve the same performance. Another consideration is thermal stability. If the sensor needs to function in extreme environmental conditions, a magnetic material with superior thermal stability must be selected. Table 3.1 below may be used to find the most suitable magnetic material as required by the application. However, Neodymium (NdFeB) is recommended for most applications.

Table 3.1: Table of Comparison of Magnetic Materials [2],[3]

Property	Lowest	Low	High	Highest
Energy Product	Ferrite	AlNiCo	SmCo	NdFeB
Holding Power	AlNiCo	Ferrite	SmCo	NdFeB
Hardness	SmCo	Ferrite	NdFeB	AlNiCo
Corrosion / Rust Resistance	NdFeB	AlNiCo	SmCo	Ferrite
Thermal Stability	NdFeB	SmCo	Ferrite	AlNiCo
Cost	Ferrite	AlNiCo	NdFeB	SmCo

3.5 Magnet Grading

Magnet grading refers to the strength rating or energy product of the magnet [4]. A higher grading or 'N' number is indicative of a stronger magnet. Table 3.2 below specifies the maximum energy product per magnet material and correlates with the energy product ratings of Table 3.1. Azoteq recommends a magnet grade of N40.

Table 3.2: Table of Magnet Gradings for Different Magnet Materials [4]

Material	Grading
Neodymium Iron Boron (NdFeB)	N35 - N52
Samarium Cobalt (SmCo)	N26
Aluminium Nickel Cobalt (AlNiCo)	N5.4
Ferrite	0.8 - 5.3

4 On-Axis Hall-Effect Sensor Design Guide

4.1 IC Selection

For on-axis Hall-effect rotation sensing, Azoteq recommends using the IQS7221E IC. The IC has four integrated Hall-effect plates for optimal rotation sensing. For more information, please refer to its datasheet.

4.2 Magnet Positioning

Figure 4.1 illustrates the optimal positioning of a magnet above the IC. Note that the magnet shown here is a solid disc type and has no inner hole, referred to as a disc magnet. Azoteq strongly recommends the use of a disc magnet for on-axis rotation, since the use of ring magnets may cause rotation dead spots. If the use of disc magnets is not possible in your application, please contact Azoteq for assistance.

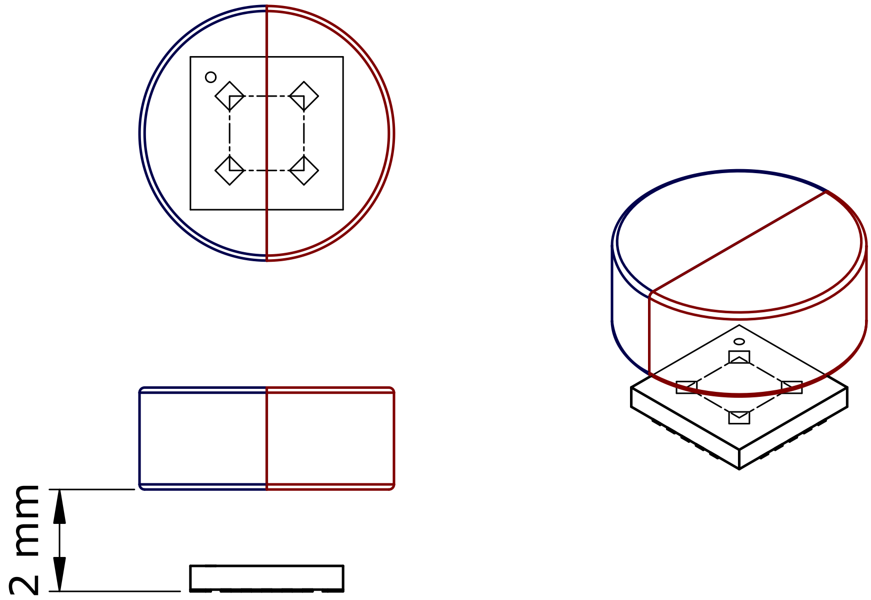


Figure 4.1: Magnet Position Relative to IC for On-Axis Orientation

4.2.1 Magnet Height h

The h dimension is also shown in Figure 4.1. While shown as 2 mm in the figure, the height typically varies between 1 and 3 mm. The height at which the magnet is placed will be influenced by the characteristics of the magnet.

As briefly explained in Section 2.1, a magnet that is closer to the Hall-effect plates will cause more magnetic flux to influence the plates. The magnet height therefore strongly dictates the quality of measurement. To enable the IQS7221E to make accurate measurements, the magnetic flux density measured by the Hall-effect plates should be at minimum 20 mT and most 100 mT.

Figure 4.2 shows how the maximum magnetic flux density changes with different magnet strengths, at different heights. The example shown here is specifically for a 5x2 mm disc magnet.

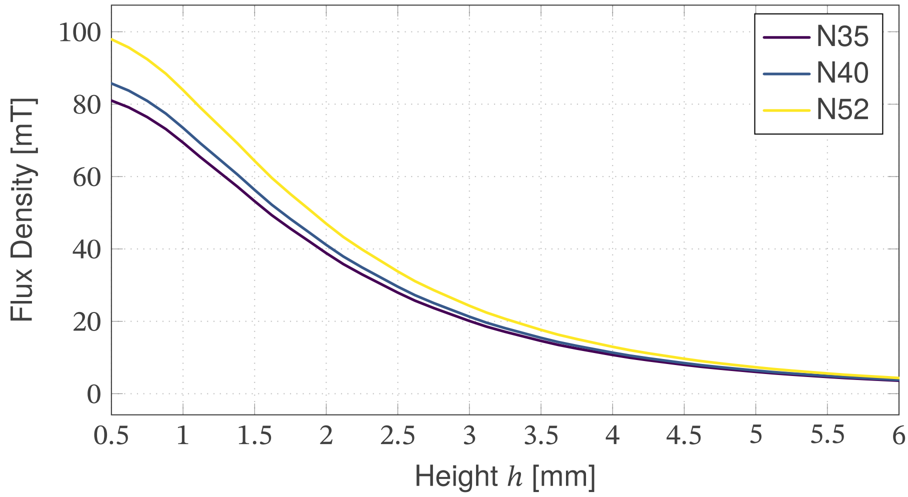


Figure 4.2: Magnetic Flux Density vs Magnet Distance and Grading (5x2 mm Magnet)

Distance has the most significant effect on the measured flux density. Using a stronger magnet does allow for the magnet to be positioned further away from the IC, but Figure 4.2 suggests that no more than 0.5 mm of extra height can be gained.

Also, note that most magnets more than 3 mm above the PCB are unlikely to provide adequate magnetic field strength for accurate angle measurements.

4.2.2 Magnet Lateral Offset

In Figure 4.1, the magnet is positioned such that the centre of the magnet aligns exactly with the centre of the IC. However, in practice, the centres will likely be misaligned by some offset distance, due to either manufacturing tolerances or application restrictions. Figure 4.3 below illustrates the concept.

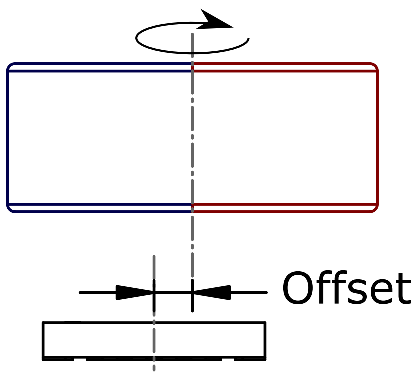


Figure 4.3: Illustration of Magnet Misalignment

The result of this is that the Hall-effect plates do not receive identical magnetic flux amplitudes. Plates further away from the magnet may experience a weaker or stronger magnetic field (depending on the system geometry) than plates closer to the magnet. This causes errors in the calculated angle and by extension, reduces linearity.

The effect of magnet offset is also a function of vertical distance. At close distances a small offset can appear relatively large, causing larger errors. However, if the magnet is too far away (more than

3 mm), the Hall-effect sensors may not measure enough signal to calculate an accurate angle.

Figure 4.4 and Figure 4.5 show the effects of magnet offsets vs diameter and distance on the resulting linearity of the Hall-effect rotation measurement.

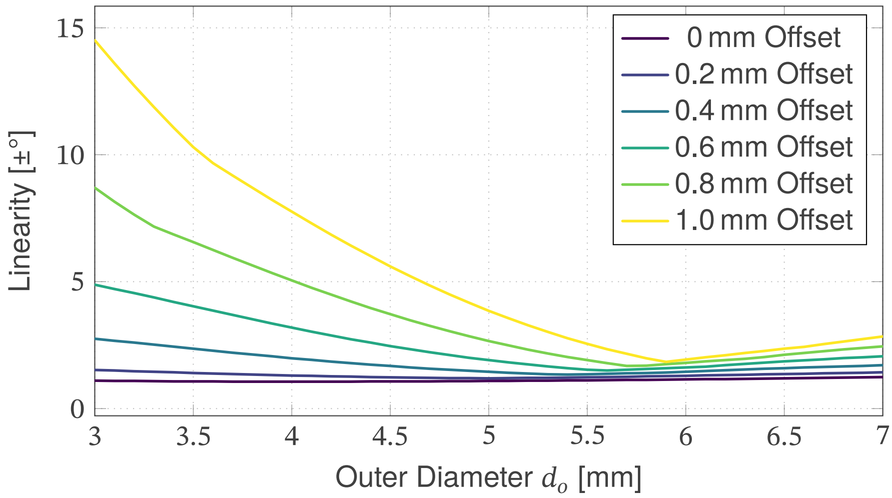


Figure 4.4: Linearity vs Magnet Diameter and Offset (N40, $w = 2$ mm, $h = 1.5$ mm)

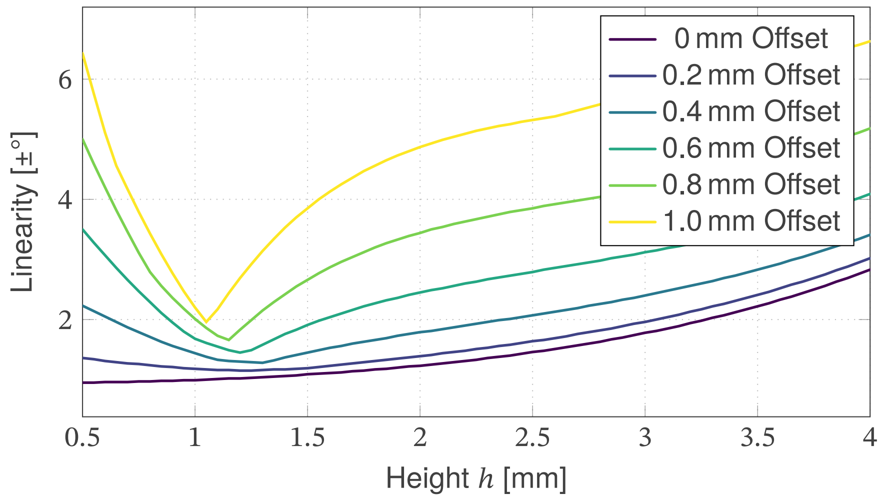


Figure 4.5: Linearity vs Magnet Distance and Offset (N40, $w = 2$ mm, $d_o = 5$ mm)

Figure 4.4 shows that magnets with smaller diameters are highly sensitive to positioning errors. It suggests that the optimal magnet diameter is approximately 6 mm. At distances under 1 mm the system becomes highly sensitive to offset, and at distances above 3 mm the combination of the offset and the low flux density also contributes to poor linearity.

4.2.3 Magnet Wobble

Another magnet positioning characteristic that influences linearity is magnet wobble, which occurs when the magnet does not rotate precisely around its centre. The axis of rotation is offset from the centre of the magnet. This causes the magnet to move closer and further away from the Hall-effect plates periodically. Figure 4.6 illustrates the concept.

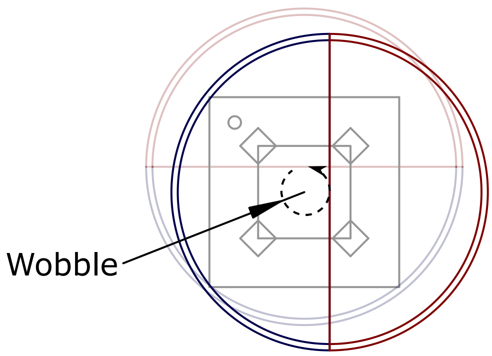


Figure 4.6: Illustration of Magnet Wobble

Figure 4.7 and Figure 4.8 show the effects of magnet diameter and distance on the resulting linearity of the Hall-effect rotation measurement.

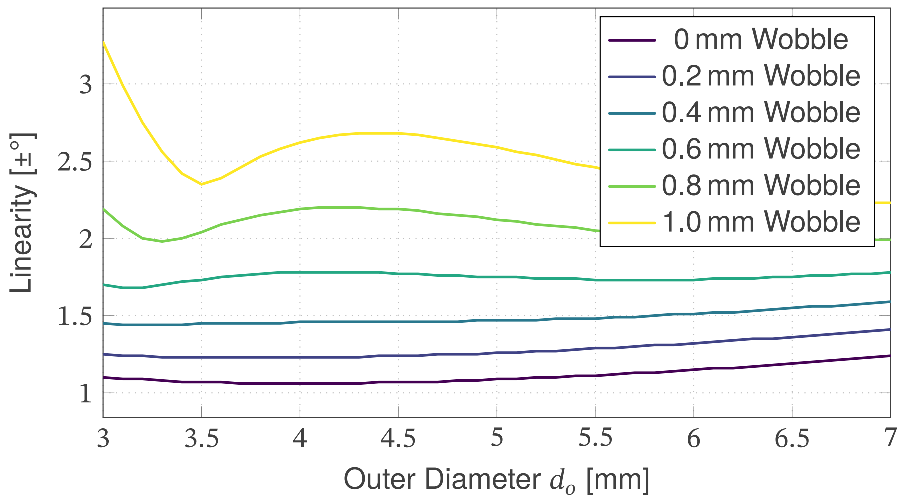


Figure 4.7: Linearity vs Magnet Diameter and Wobble (N40, $w = 2\,\text{mm}$, $h = 1.5\,\text{mm}$)

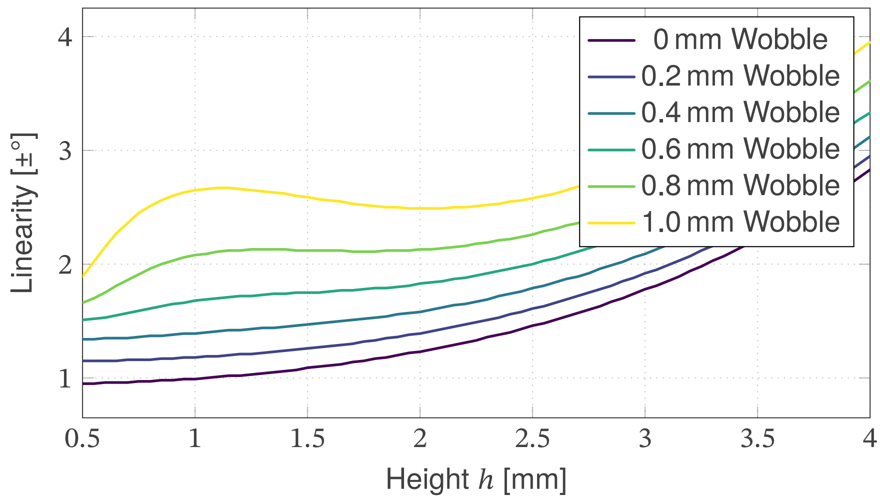


Figure 4.8: Linearity vs Magnet Height and Wobble (N40, $w = 2\,\text{mm}$, $d_o = 5\,\text{mm}$)

For all the cases above, the linearity of the sensor remained under 4°, even with extreme wobble.

Thus, wobble has minimal impact on the accuracy of the output angle, at least for on-axis applications. This is primarily because the effects of the wobble tend to cancel out in on-axis angle calculations. However, wobble can compound the effect of existing offset errors, potentially causing large linearity errors. It is therefore recommended that sufficient design effort is made to minimize wobble as far as possible.

4.3 Magnet Outer Diameter d_o

Figure 4.9 shows how the magnet's diameter affects the maximum z-component flux density measured, and at different distances. Larger-diameter magnets tend to provide a flatter curve over distance, making the system less sensitive to variation in vertical distance. However, they tend to expose the Hall-effect plates to less magnetic flux. Smaller-diameter magnets may offer higher flux densities but will be more sensitive to mechanical tolerances. Within the range of d_o considered here, it is recommended to use a larger-diameter magnet.

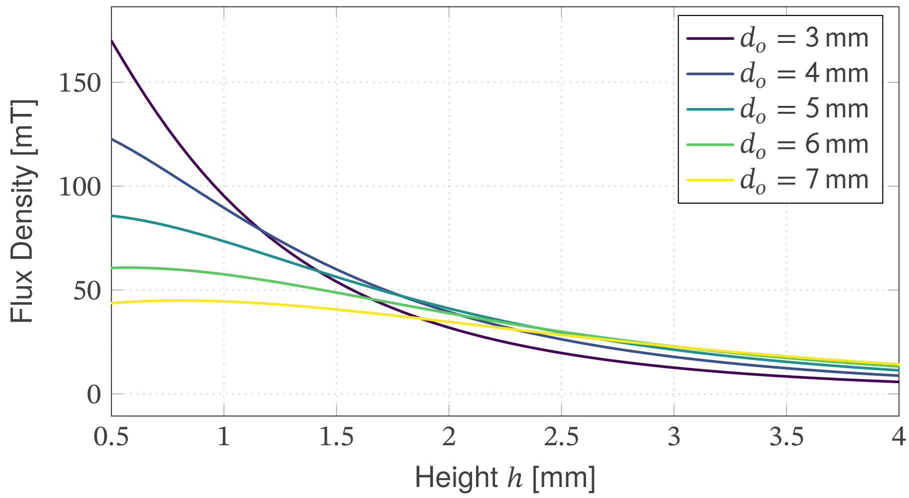


Figure 4.9: Magnetic Field Density vs Magnet Distance and Diameter (N40, $w = 2\,\text{mm}$)

4.4 Magnet Width w

Figure 4.10 shows the effect of changing thickness and distance for a 5 mm diameter magnet.

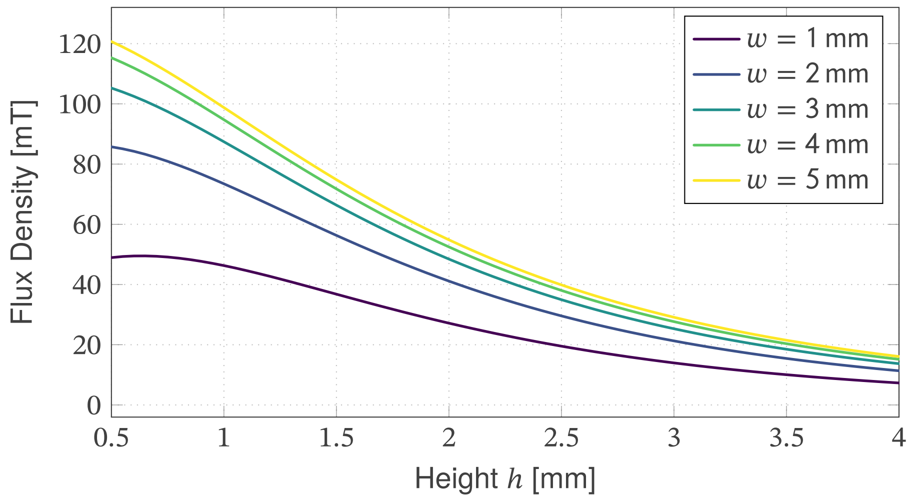


Figure 4.10: Magnetic Field Density vs Magnet Distance and Thickness (N40, $d_o = 5\,\text{mm}$)

Larger thicknesses provide greater signal strength. However, increasing the magnet thickness beyond 3 mm has diminishing returns.

4.5 Design Summary

Table 4.1 provides a summary of the typical parameters that were described in Sections 4.2 to 4.4. It is emphasized that these parameters are typical values and their applicability should be verified before final design implementation, by consulting the appropriate application note.

Table 4.1: Summary of Typical Parameters for On-Axis Hall-Effect Configuration

Variables	Typical Value	Reference
Height Above PCB (h)	1 - 3 mm	Section 4.2.1
Outer Diameter (d_o)	5 mm (6 mm if offsets are expected)	Section 4.3 Figure 4.4
Width (w)	2-3 mm	Section 4.4
Magnet Material	NdFeB	Section 3.4
Magnet Grading	N40	Section 3.5
Residual Induction (B_r)	1.25 T	N/A
Polarization	Diametrical	N/A

5 Off-Axis Hall Sensor Design Guide

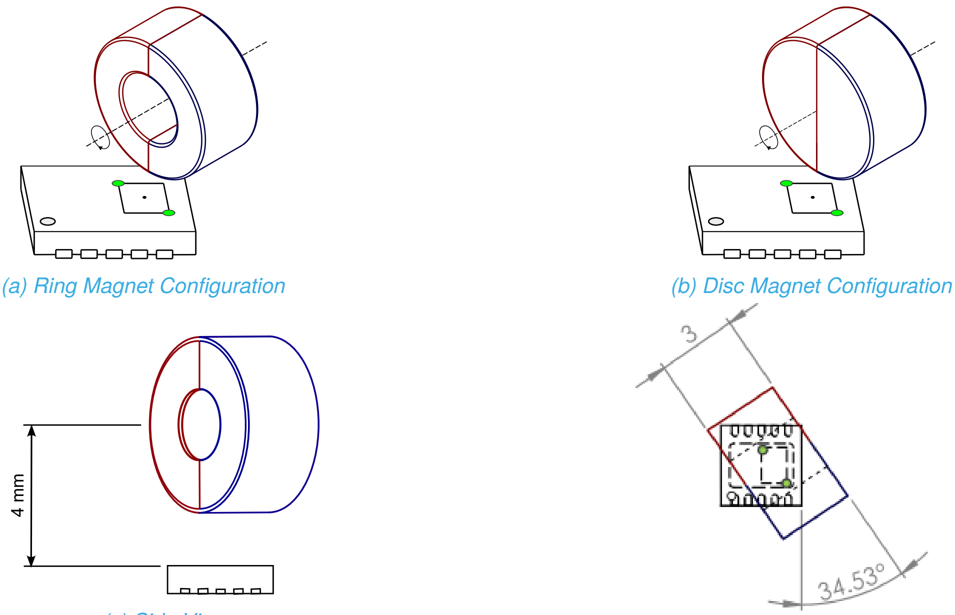
5.1 IC Selection

For off-axis hall rotation sensing, Azoteq recommends using the IQS624 IC. The IC has two integrated hall plates for optimal rotation sensing. For more information, please refer to its datasheet.

5.2 Axis-parallel Configuration

5.2.1 Magnet Positioning

Figure 5.1 illustrates the optimal positioning of a ring and disc magnet above the IC. Note that the hall plates (indicated by the green spots on the top view) are diagonally placed on the IC. Thus, the magnet must be placed at a 34.53° angle relative to the IC, as shown in the figure. While both the ring magnet and disc magnets may be used for the axis-parallel configuration, the disc magnet is the preferred choice since it provides more magnetic field strength for the same magnet size.



(a) Ring Magnet Configuration

(b) Disc Magnet Configuration

(c) Side View

(d) Top View

Figure 5.1: Illustration of Off-Axis (Axis-Parallel) Orientations Relative to the IC

5.2.2 Magnet Height h

Similar to on-axis, distance has the biggest effect on magnetic flux density, while magnet strength has a minimal practical improvement. For most magnets, the magnet should be positioned within 4-5 mm of the PCB.

It should be noted that a trade-off exists between having high field strength and magnet wobble resistance. If h is low, the Hall-effect plates will be exposed to high magnetic flux density and will therefore have good signal. However, because of the magnet's close proximity to the IC, any wobble effect will be significant (Refer to Section 5.2.5 for wobble explanation). Conversely, a high h will decrease signal strength and increase wobble resistance.

5.2.3 Phase Angle and Jitter

With reference to Section 3.3, the designer should ensure that the off-axis configuration has a sufficiently large phase angle to minimise jitter.

5.2.4 Magnet Lateral Offset

In the off-axis case, magnet offset refers to the positioning error between the centre of the IC and the centre of the magnet, as shown in Figure 5.2. The magnet rotates in place, but is closer to one Hall plate than the other, causing the plates to measure different amplitudes. For best performance, the lateral offset should be minimised.

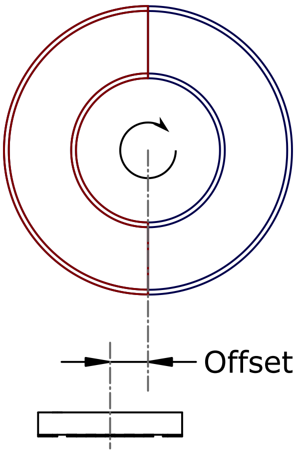


Figure 5.2: Illustration of Magnet Misalignment

5.2.5 Magnet Wobble

The same definition for wobble used for on-axis applications apply to off-axis applications – it occurs when the magnet does not rotate precisely around its centre axis. The axis of rotation is therefore offset from the centre of the magnet. This causes the magnet to move closer and further away from the Hall plates periodically, and is illustrated in Figure 5.3.

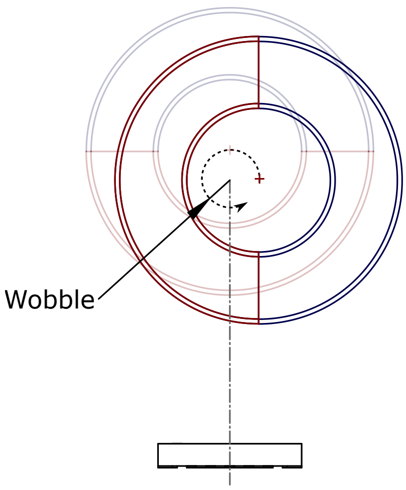


Figure 5.3: Illustration of Off-axis Magnet Wobble

In contrast to an on-axis system, the off-axis configuration is highly susceptible to any amount of wobble that the magnet may exhibit. A wobble amplitude of only 0.2 mm introduces a significant error. This can be somewhat mitigated by positioning the magnet further away from the IC, but this improvement is not substantial. Much stricter mechanical tolerances have to be placed on the design of off-axis rotation sensors than their on-axis counterparts.

5.2.6 Magnet Inner Diameter d_i and Outer Diameter d_o

Larger-diameter magnets significantly increase the magnetic flux density at the hall plates. Thus, a larger magnet (high d_o) may be positioned further away from the IC than smaller magnets, but will lead to a smaller phase angle. The d_i of the magnet has the reverse effect. A high d_i will reduce magnet strength, while a low d_i allows for more magnet strength, resulting in an increased allowable h.

Refer to the design guide in Section 5.2.8 for more information on the trade-offs between d_o, d_i, and h.

5.2.7 Magnet Width w

Thicker magnets improve the strength of the magnetic field measured, although there is little practical improvement by exceeding a width of 4 mm. As per Figure 5.1, the recommended width is 3 mm.

5.2.8 Configuration Guide

Figure 5.4 below may be used as a design tool to help the designer determine the optimal dimensions for the magnet d_o, d_i and h, in the case of a ring magnet. The figure assumes the maximum allowable magnetic flux (100 mT) using an N40 NdFeB ring magnet.

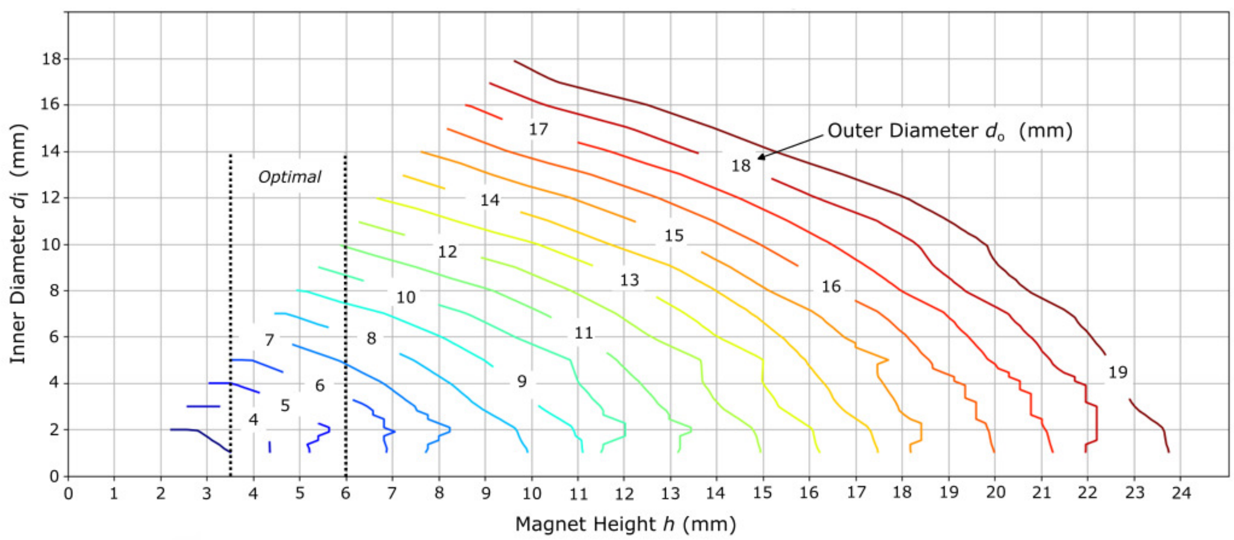


Figure 5.4: Magnet Outer Diameter as a Function of Inner Diameter and Height for N40 NdFeB at 100 mT

The designer should choose two design variables according to the application or geometry restrictions and use Figure 5.4 to select the third variable. For example, if it is known that the magnet to be used has d_o = 6 mm and d_i = 5 mm, then the optimal h is 4 mm above the PCB.

If the graph does not satisfy the requirements of the application, the designer must re-iterate the process to find a magnet that will fit the application. Note that the optimal h for magnet placement is demarked on Figure 5.4 to be between 2 and 5 mm since this is the range where the optimal phase angle is found. If the magnet axis is placed outside of this range, the signal quality will not be sufficient.

5.2.9 Design Summary

Table 5.1 provides a summary of the typical parameters that were explained in Sections 5.2.1 to 5.2.8. It is emphasized that these parameters are typical values and their applicability should be verified before final application implementation.

Table 5.1: Summary of Typical Parameters for Off-Axis Hall Configuration

Variables	Typical Value	Reference
Height above PCB (h)	3.5 - 6 mm (Consult design guide)	Section 5.2.2 Figure 5.4
Outer Diameter (d_o)	5 - 6 mm (Consult design guide)	Section 5.2.6 Figure 5.4
Inner Diameter (d_i)	0 - 4 mm (Consult design guide)	Section 5.2.6 Figure 5.4
Width (w)	2 - 3 mm	Section 5.2.7
Magnet Material	NdFeB	Section 3.4
Magnet Grading	N40 - N52	Section 3.5
Residual Induction (B_r)	1.25 T	N/A
Polarization	Diametrical	N/A

5.3 Axis-perpendicular Configuration

For the axis-perpendicular configuration, the same general principles discussed in Section 5.2 apply.

Figure 5.5 illustrates the placement of the magnet. It is shown that for the axis-perpendicular configuration, the typical magnet placement height h is 2 mm, which is lower compared to the typical h of the axis-parallel version. Its typical d_o dimension is 8 mm, and the magnet width w is 2 mm. The inner diameter is not applicable here, as it is strongly recommended to use disc magnets for this configuration. Finally, the same magnet material and strength recommendations apply. Table 5.2 provides a summary of the typical axis-perpendicular parameters.

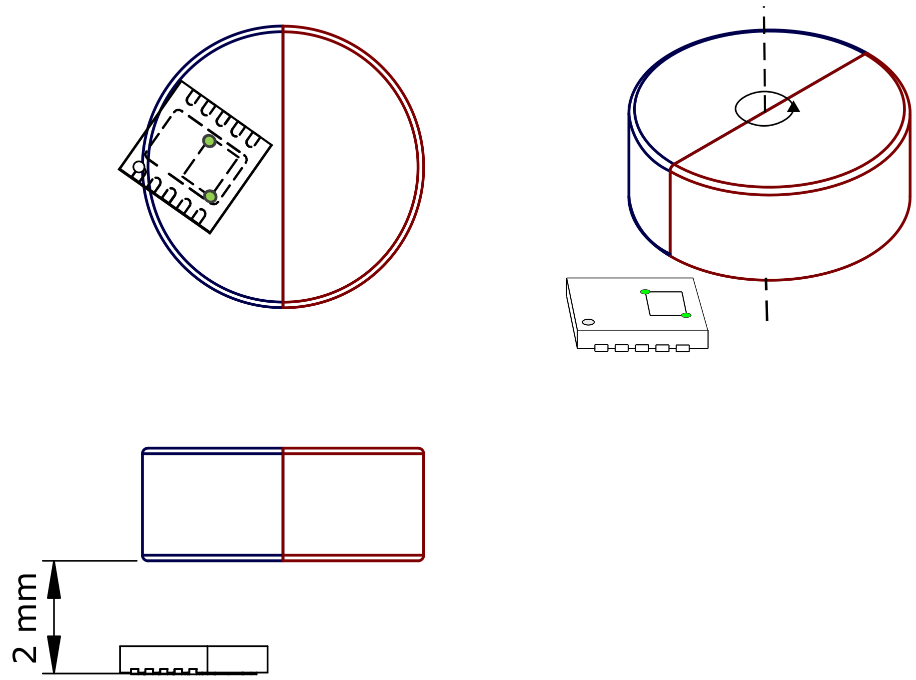


Figure 5.5: Magnet Position Relative to IC for Off-Axis (Axis-Perpendicular) Orientation

Table 5.2: Summary of Typical Parameters for Off-Axis (Axis-Perpendicular) Hall Configuration

Variables	Typical Value
Height above PCB (h)	2 mm
Outer Diameter (d_o)	8 mm
Inner Diameter (d_i)	N/A
Width (w)	2 mm
Magnet Material	NdFeB
Magnet Grading	N40 - N52
Polarization	Diametrical

6 Conclusion

This document described and explained guidelines for using the IQS7221E and IQS624 for Hall-effect rotation sensing, in the on-axis and off-axis configurations respectively. It is emphasised that values given in this document are *not* application specific, but rather boundary approximations for good design. Please refer to the applicable application note for application-specific recommendations.

For queries regarding the content of this document, please contact Azoteq for assistance.

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Contact Information

	USA	Asia	South Africa
Physical Address	11940 Jollyville Suite 120-S Austin TX 78759 USA	Room 501A, Block A T-Share International Centre Taoyuan Road, Nanshan District Shenzhen, Guangdong, PRC	1 Bergsig Avenue Paarl 7646 South Africa
Postal Address	11940 Jollyville Suite 120-S Austin TX 78759 USA	Room 501A, Block A T-Share International Centre Taoyuan Road, Nanshan District Shenzhen, Guangdong, PRC	PO Box 3534 Paarl 7620 South Africa
Tel	+1 512 538 1995	+86 755 8303 5294 ext 808	+27 21 863 0033
Email	info@azoteq.com	info@azoteq.com	info@azoteq.com

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