Application note

Dual-Disk Linear Stray field Robust Position Sensing

Content

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1. Introduction

About half of the six billion magnetic sensors shipped each year are for the automotive market[1]. That same market gradually electrifies, and with it, the importance of stray field rejection methods grows too. Angle sensors play a significant role in engine control, steering, and numerous other applications such as pedal, wipers, gearshift applications, and many more. Besides angle sensing, linear displacement sensing is also of interest in this industry.

In this application note, we address this interest. We introduce new designers to the Melexis concept for stray field rejection, often also referred to as stray field robustness or stray field immunity for linear applications. We aim to help a designer to define a suitable magnet according to a set of applications requirements and provide a list of reference magnet designs. In the following chapter, we elaborate in detail on the most crucial design aspects. Pay attention that the case studies might be subjected to patent constraints.

2. Scope

In the first chapter, we explain the concept of Melexis's stray field robustness method. The next chapters put the focus on the step-by-step design process. Finally, we conclude with recommendations. The concept methodology is valid for both MLX9037x and MLX90423; however, in this application note, we design according to the specifications of MLX90372 / 90423 and with a minimum field gradient norm of 6mT/mm at room temperature.

To understand the impact of magnet vs. sensor, we perform the following case studies:

- [case study 1] – Two-pole axial parallel cylindrical magnet;
- [case study 2] – Two-pole axial orthogonal cylindrical magnet;
- [case study 3] – Three-pole axial (sinusoidal) parallel cylindrical magnet;
- [case study 4] – Three-pole axial parallel cylindrical magnet;

3. Related documentation

MLX90371 Datasheet (download here)
MLX90372 Datasheet (download here)
MLX90423 datasheet (download here)
AN_Quick_guide_to_backend_calibration (download here)

[1] *[1] Y. de Charentenay, "Magnetic sensors market & technologies 2017," tech. rep., Yole, 2017.*

4. What is linear position sensing

Triaxis® Hall technology is sensitive to the flux density applied parallel to the IC surface. Triaxis® products are sensitive to the three components of the flux density, i.e. BX, BY, and BZ.

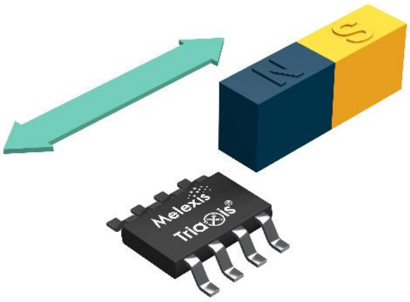

Figure 1 Linear position sensing using a two-pole axial parallel magnet

The method allows it to sense the field of a magnet moving in its surroundings, and it enables the design of innovative non-contacting linear position sensors, which is required for both automotive and industrial applications (e.g., man-machine interface). In combination with the appropriate signal processing, the magnetic flux density of a small magnet moving above the IC is measured in a non-contacting way.

Linear position sensing, which is different from linear Hall sensing, offers several benefits such as robustness to temperature variations and increased linear stroke.

To determine the relative position of magnet vs. sensor in a linear position sensing mode, typically, two magnetic field vectors are measured. These two are often Bx and Bz. The calculated angle from both vectors changes with the position of the magnet. With this method, we achieve longer strokes and eliminate any temperature effects. In contrast to the conventional linear Hall approach, only Bz is used as position input, see Figure 2.

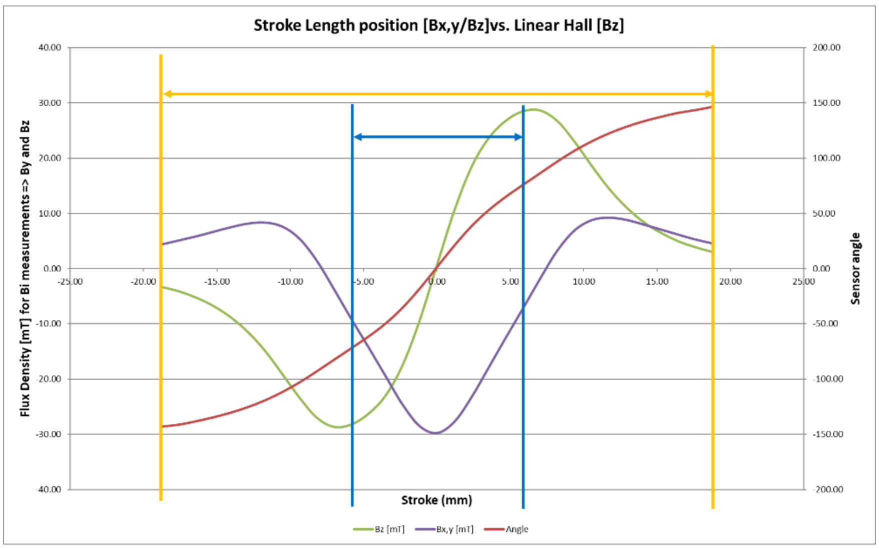

Figure 2 A comparison between the two discussed approaches; one can see that with a linear position sensing approach, the stoke is three times longer than a conventional linear Hall approach. Take note that linear Hall sensing is not immune to temperature variations.

Besides the mentioned advantages, note that the mechanical alignment between the axis of movement, magnet position, and sensor position strongly determines measurement accuracy.

That means that mechanical alignment errors can result in additional offset, amplitude change, and non-linearity vs. the ideal output curve. Whereas signal offset and signal amplitude mismatch are easily trimmed and compensated at the IC level, linearity errors derived from mechanical error or tolerances need to be compensated for through linearization of the sensor's output transfer curve.

However, any external magnetic interference, if relatively high enough, cannot be filtered or compensated for and can eventually lead to additional non-linearity errors. Melexis proposes a solution to overcome this issue in the following chapters.

5. Melexis Dual-Disk stray field robustness principle

The Dual-Disk naming originates from the fact that two IMC disks are used to measure the useful signal. A Triaxis® position sensor configured in this mode (Dual-Disk) allows the application to be robust to homogeneous stray fields. The concept of stray field robustness is explained by measuring the delta magnetic field components Bx and Bz over a fixed-pitch between both IMCs. Take note that the pitch between sensors can differ between products.

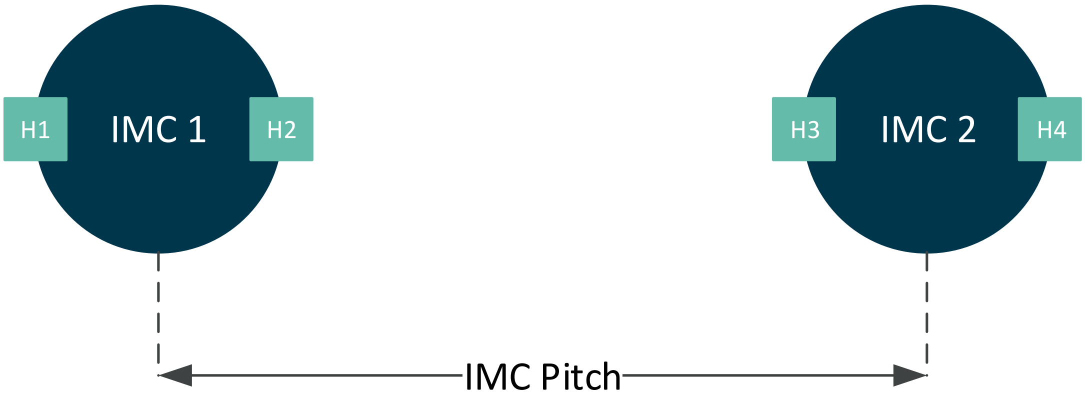

Figure 3 Distance between two IMCs

Via Hall elements (H1…4) the field components are measured. Per IMC, we have exactly two Hall-elements cfr. IMC_1\{H1,H2\} and IMC_2\{H3,H4\}. The formula below shows how to calculate each magnetic component. Please consult the datasheet for more information for the Triaxis® magnetic Hall principle.

$$\begin{cases} BX_1 = IMCgainx * (H1 - H2) \\ BX_2 = IMCgainx * (H3 - H4) \\ BZ_1 = (H1 + H2) \\ BZ_1 = (H3 + H4) \end{cases}$$

The useful signal (magnetic field gradient) is the differential result of both IMC's and is expressed in mT/mm. This differential approach consequently removes any homogeneous disturbance, i.e. stray field (SF).

In achieving stray field robustness, the applied magnetic field gradient norm to the sensor must be minimum 3mT/mm, and at least 6mT/mm to be performant. A minimum of 3mT/mm magnetic field gradient is allowed; however, designing according to the minimum specification, one must consider an increase in thermal drift and noise. For both differential components, the corresponding angle calculation is as followed:

$$\alpha = \operatorname{atan}\frac{\Delta BX}{\Delta BZ}{}^{2}$$

6. Magnet design for a Dual-Disk design approach

6.1. Dual-Disk magnetic design rules

Conditions to design a magnet using the linear stray field robust principle are listed below. These conditions must be met at all times.

Table 1 Linear stray field robustness mode

Parameter	Symbol	Min.	Typ.	Max.	Unit	Condition
Magnetic flux density in X	Bx	-	-	70	mT	MLX90371
	Bx	-		80	mT	MLX90372
Magnetic flux density in Z	Bz	-	-	100	mT	
Magnetic gradient of X-Z Field components	$\frac{\Delta B_{xz}}{\Delta x}$	3	6	-	mT/mm	$\sqrt{\left[\left(\frac{\Delta Bx}{\Delta X}\right)^2 + \left(\frac{1}{G_{IMC}}\frac{\Delta Bz}{\Delta X}\right)^2\right]}$
IMC gain[3]	G_{IMC}	-	1.19	-		Applicable to X and Y Hall plates
Parameter	Symbol	Min.	Typ.	Max.	Unit	Condition
IMC pitch	Δx	-	1.8	-	mm	MLX90371
			1.91			MLX90372+,MLX90423

Be advised to check the latest datasheet.

6.2. Magnetic fields and Dual-Disk definition

We consider the “bias field” as the field generated by the magnet; This field is seen by the sensor at an individual IMC-level and consists out of two components; a common component parallel to the surface of the sensor, and a differential component orthogonal to the surface. The gradient field is the result of the field vector differentiation from both IMC locations. In Dual-Disk mode, we consider the gradient field as our useful field as opposed to the common component.

In a perfect scenario, the differential measurement approach cancels the common component as seen by the sensor but due to small sensitivity variations between the Hall-plates the common component is not completely removed. The resultant eventually leads to an additional error. The new product MLX90423, based on the midrange platform with 8 HEs in total, implementing an improved dual disk concept to reduce this thermal drift error vs MLX9037x. The formula below describes this effect as the thermal bias error[4]., which is the discussed error within the temperature range of -40° to 160°.

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[2] ΔBX = Bx1 – Bx2, ΔBZ = Bz1 – Bz2

[3] IMC gain ration between X and Z is 1.19 to 1

[4] Bias field norm $|B|$ represents the field norm between X and Z. Gradient field norm $\left|\frac{\delta B}{\delta x}\right|$ represents field norm between ΔBx,z/ΔX.

$$\Delta\theta \cong \frac{|B|}{\left|\frac{\delta B}{\delta x}\right|}.0.6 \text{ (MLX9037x)} \qquad \Delta\theta \cong \frac{|B|}{\left|\frac{\delta B}{\delta x}\right|}.0.2 \text{ (MLX90423)}$$

It's in the interest of the designer to design such that enough gradient field norm is available to diminish the additional thermal error. This thermal error must be taken into account in the designer's total error budget as it's not possible to compensate for this error via the conventional back-end-calibration methods.

Table 2 is an excerpt from the datasheets and highlights the thermal error contributors. It's not possible to trim thermal errors.

Table 2 Linear stray field immune magnetic performances

	Parameter	Symbol	Min.	Typ.	Max.	Unit	Condition
Sensor (part of datasheet)	XZ - Intrinsic Maximum Error	L_{E_XZ}	-2.5 -1.5	±1.25	2.5 1.5	Deg.	MLX90371 MLX90372, MLX90423
	Noise[5]		-	0.1	0.2	Deg.	90372 ,Filter = 1, 6mT/mm
				0.15	0.3		90372, Filter = 0, 6mT/mm
				-	0.25		90372, Filter = 0, 6mT/mm, T_{max}=125°C
	XZ - Total Drift [6]	$\partial\theta_{TT\_XZ}$	-0.8 -0.6 -0.8		0.8 0.6 0.8	Deg.	90372, re; to 35°C, 6mT/mm, B/dB=0 90423, rel. to 35°C, 6mT/mm, B/dB=0 90423, rel. to 35°C, 6mT/mm, B/dB=3
	Hysteresis		-	-	0.1	Deg	6mT/mm gradient field
	IMC gain	G_{IMC}	-	1.19	-		
	Output Stray Field Immunity	$\partial\theta_{FF}$	-	-	0.8 0.4	Deg.	90372, 6mT/mm and 4kA/m stray field [7] 90423, 6mT/mm and 4kA/m stray field
	Output Stray Field Immunity	$\partial\theta_{FF}$	-	-	0.2	Deg.	For 6mT/mm gradient field and 1kA/m stray field [7]
Magnet	Thermal bias error[8]	$\Delta\theta$	In function of the magnet			Deg.	Maximum error considering a temperature range -40° to 160°.

Be advised to check the latest datasheet.

Additional note on bias field versus stray fields

Bias fields are not be confused with stray fields. Stray fields typically coming from a current feeding wire are many times smaller than magnet bias fields. For example, a current-carrying wire driving 4000 A/m can generate up to 5mT on the contrary, the bias field in a typical linear application can reach up to 70 mT[9].

[5] ±3σ

[6] Verification done on new and aged devices in an ideal magnetic field gradient. An additional application specific error arises from the non-ideal magnet and mechanical tolerance drift.

[7] Tested in accordance with ISO 11452-8:2015, at 30°C, with stray field strength of 4kA/m from any direction. This error scales linearly with both the useful field and the disturbing field.

[8] Error is depending on the dimensions & characteristics of the magnet. The error represents the max total drift taken from -40 to 160 DegC

[9] Depending on magnetic characteristics and air gap. The field reduces at the edges of the magnet and stroke.

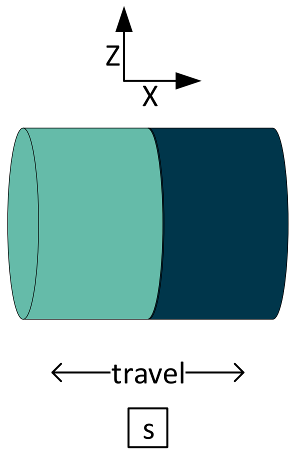
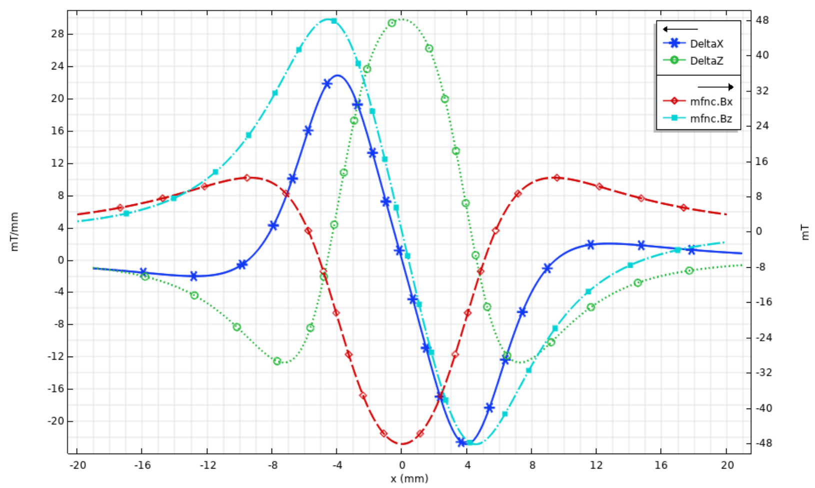
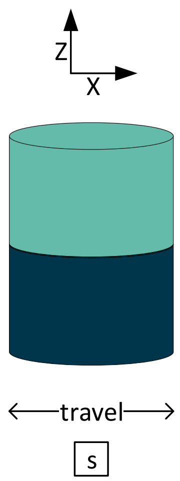
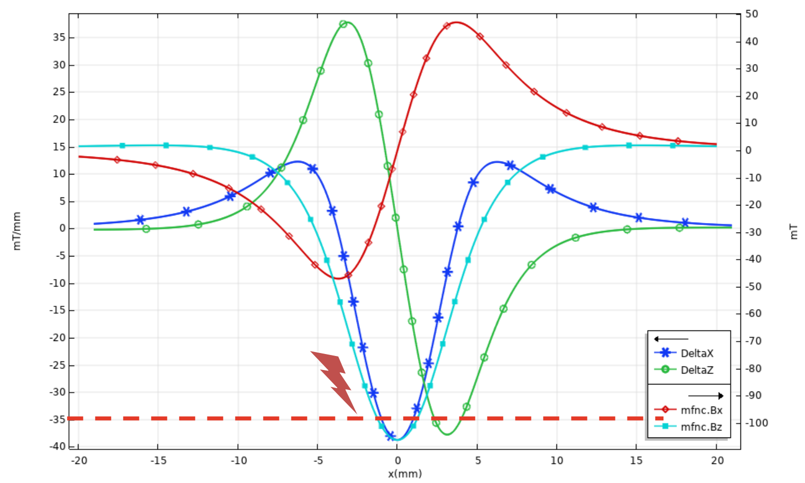
6.3. Step by step magnetic design approach

The following chapter elaborates step by step on the most basic design checks.

6.3.1. Bias field check and gradient field evaluation

Table 3 gives two hypothetical reference examples; these represent the behavior of the bias and gradient field. First, we illustrate a two-pole axial parallel magnetized magnet and second a two-pole axial orthogonal magnet. The goal of these illustrations is two-fold, first to check the magnet strength versus the maximum sensor limits and second to understand the magnetic gradient pattern.

Table 3 Bias and gradient field patterns over stroke (deltaX/Z represent the differential components of BX and BZ). Note that to focus on, and to illustrate the magnetic behavior no physical dimensions are denoted.

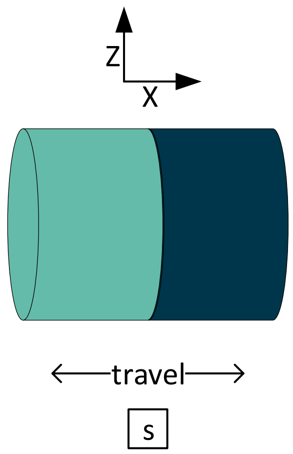
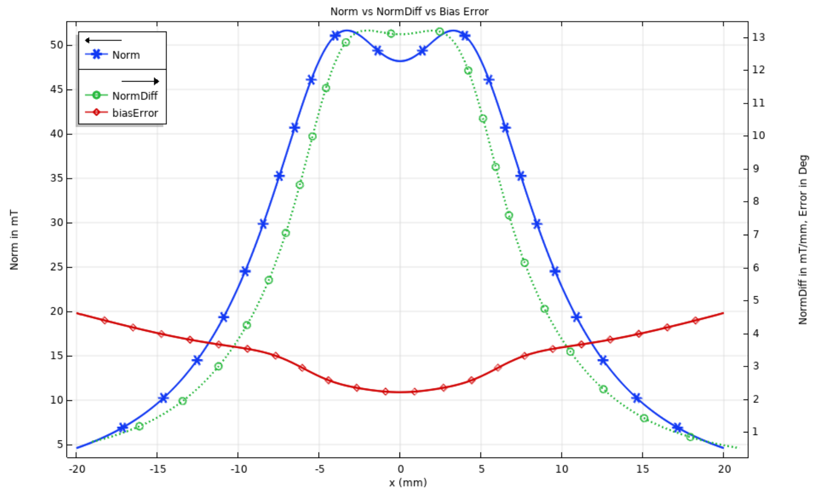
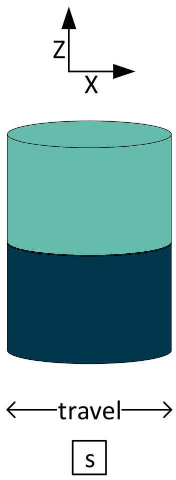
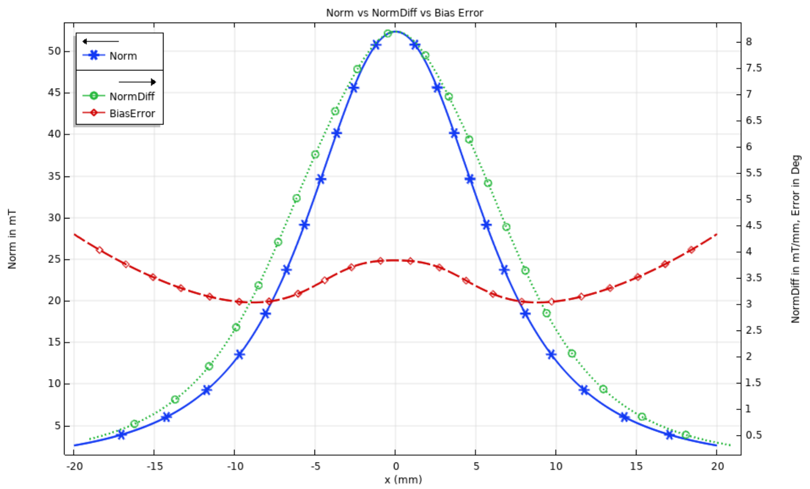
	Magnet type	Gradient and bias field
Two-pole axial parallel		
Two-pole axial orthogonal		

It's important **not to exceed the limit of the bias field**. In the example of the two-pole axial orthogonal magnet, one can see that the field Bz exceeds the maximum of 100 mT. The bias field must respect at all times the maximum limits.

6.3.2. Field norm, gradient field norm, and bias error check

Table 4 shows the behavior of the field norm and gradient field norm and its relationship with the thermal bias error. The stroke and error are limited to the acceptance level of the designer. Designing for 6mT/mm gradient field norm yields a lower stroke. However, the designer is free to go as low as 3mT/mm, with the consequence on reduced performance.

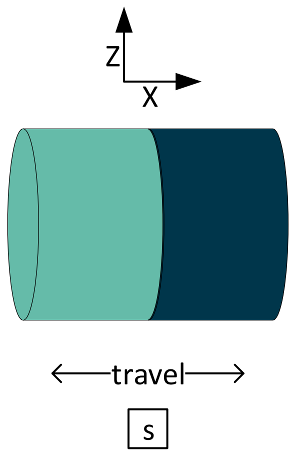
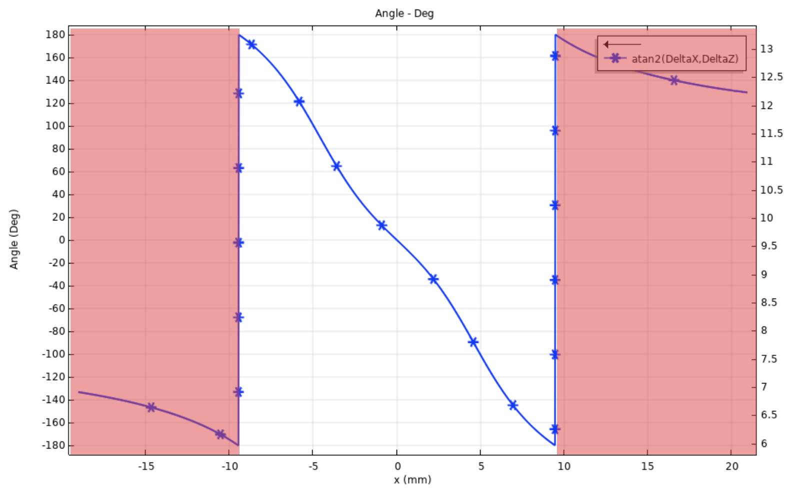
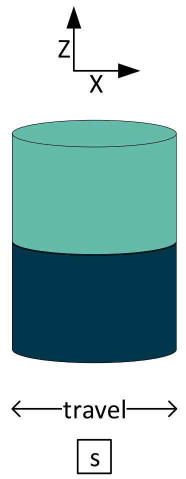
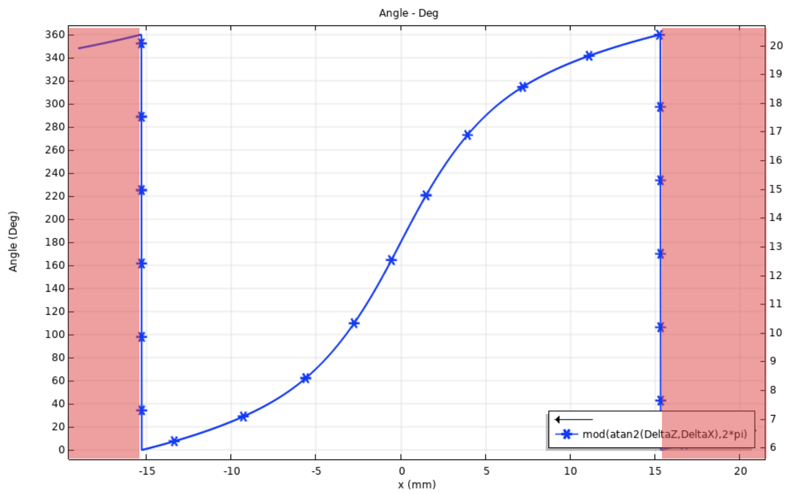
Table 4 Norm and gradient norm vs. bias error.
Note that to focus on, and to illustrate the magnetic behavior no physical dimensions are denoted.

	Magnet type	Gradient and bias field
Two-pole axial Parallel		
Two-pole axial orthogonal		

6.3.3. Sensor angle vs. application stroke check

Not only is the stroke limited to the minimum allowed gradient field norm but also to the range wherein all reported angles on the stroke are unique, as shown in Table 5. The areas marked in red form useless data as the angle is not unique for its position. Often this is referred to as angle roll-over area (2π–jump) and is to be avoided at all costs.

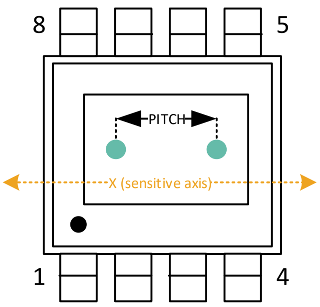
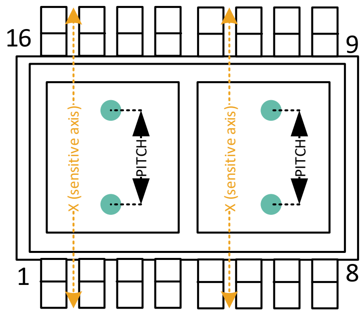
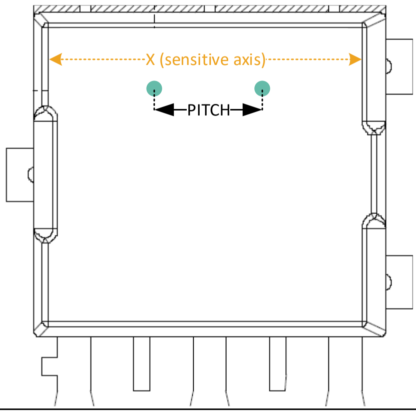
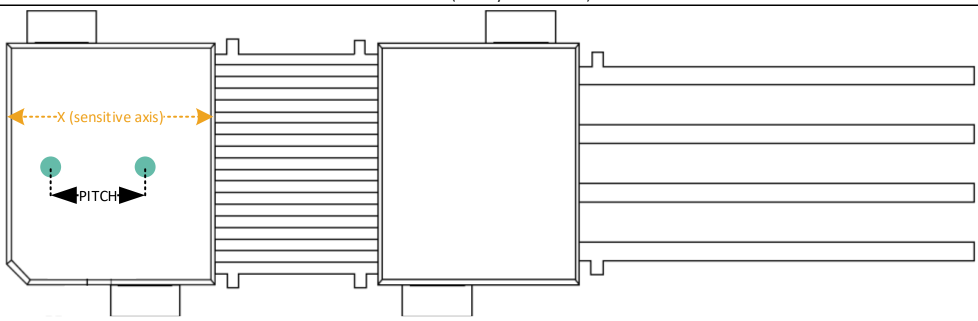
Table 5 Angle versus stroke.

	Magnet type	Angle versus stroke
Two-pole axial Parallel		
Two-pole axial orthogonal		

6.4. Mechanical positioning

Table 6 shows the magnet's axis of movement relative to the available packages. For exact dimensions, please refer to the datasheet.

Table 6 Dual-Disk sensitive axis versus package

	SOIC-8	TSSOP-16	SMP3 (only for MLX90377, 90423)
9037x & 90423			
	DMP (only 9037x)		
			

Be advised to check the latest datasheet.

7. [Case study 1] Two-pole axial parallel cylindrical magnet

In a first case study, we characterize a standard two-pole axial parallel magnet.

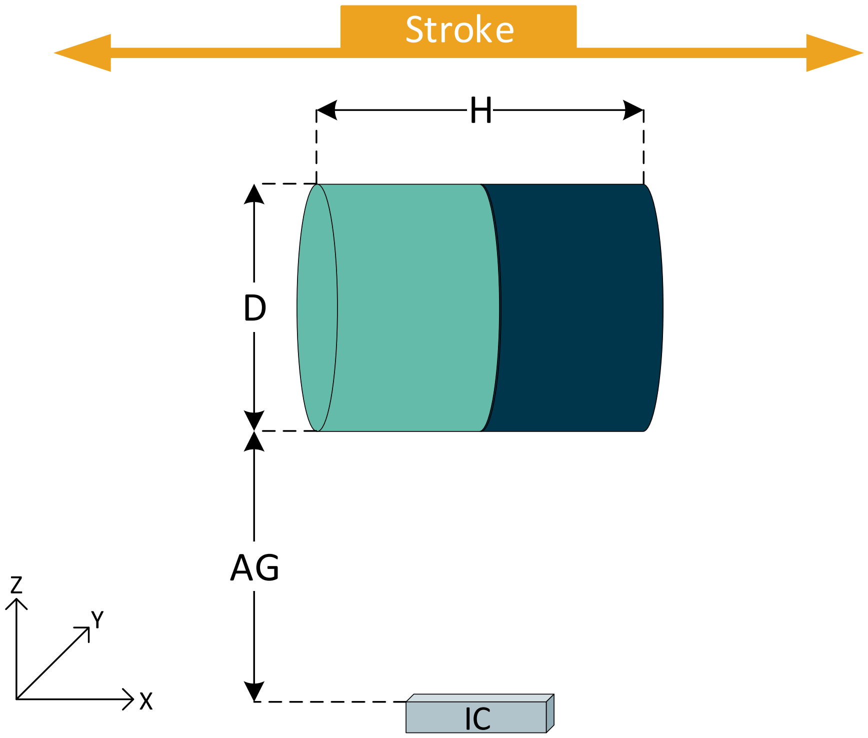


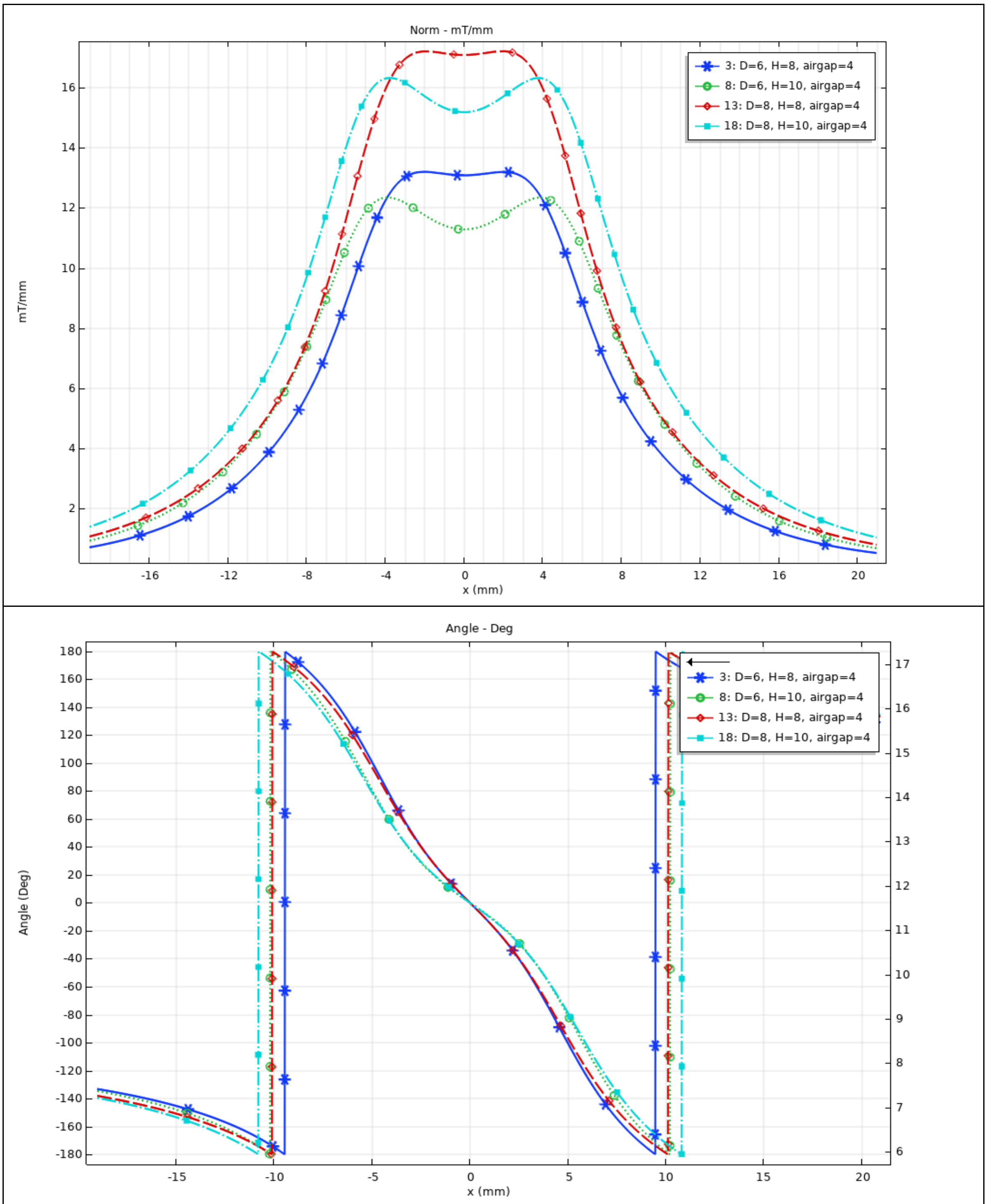
Figure 4 Two-pole axial parallel cylindrical magnet

Table 7 Magnet characteristics for a two-pole axial parallel cylindrical magnet

Magnet characteristics	Value	Remarks
Strength	1300 mT (NdFeB)	
Dimensions	D=6mm / H=8mm	*Ref. magnet selection guide MLX90333*
Magnetization	axial, along the x-axis	
Environmental conditions	Value	*Remark*
Air gap (AG)	4mm	*Typical simulation air gap*
XY-Tilt	0 Deg	
ZX Tilt	0 Deg	

Simulation abbreviation:
NormDiff: Magnetic gradient of X-Z Field components

7.1. The effect of magnet dimensions versus the field norm and the sensor output angle



The total relevant stroke is the area in which the useful sensor field does not drop below 6mT/mm (or 3mT/mm) and where the stroke only has unique sensor output angles (no roll-over).

The plots illustrate that the magnet's diameter **(D)** has a dominant effect on the field gradient norm and that the sensor's angle range increases both for increasing diameter and length.

Figure 5 The effect of magnet dimensions versus the field norm and the sensor output angle

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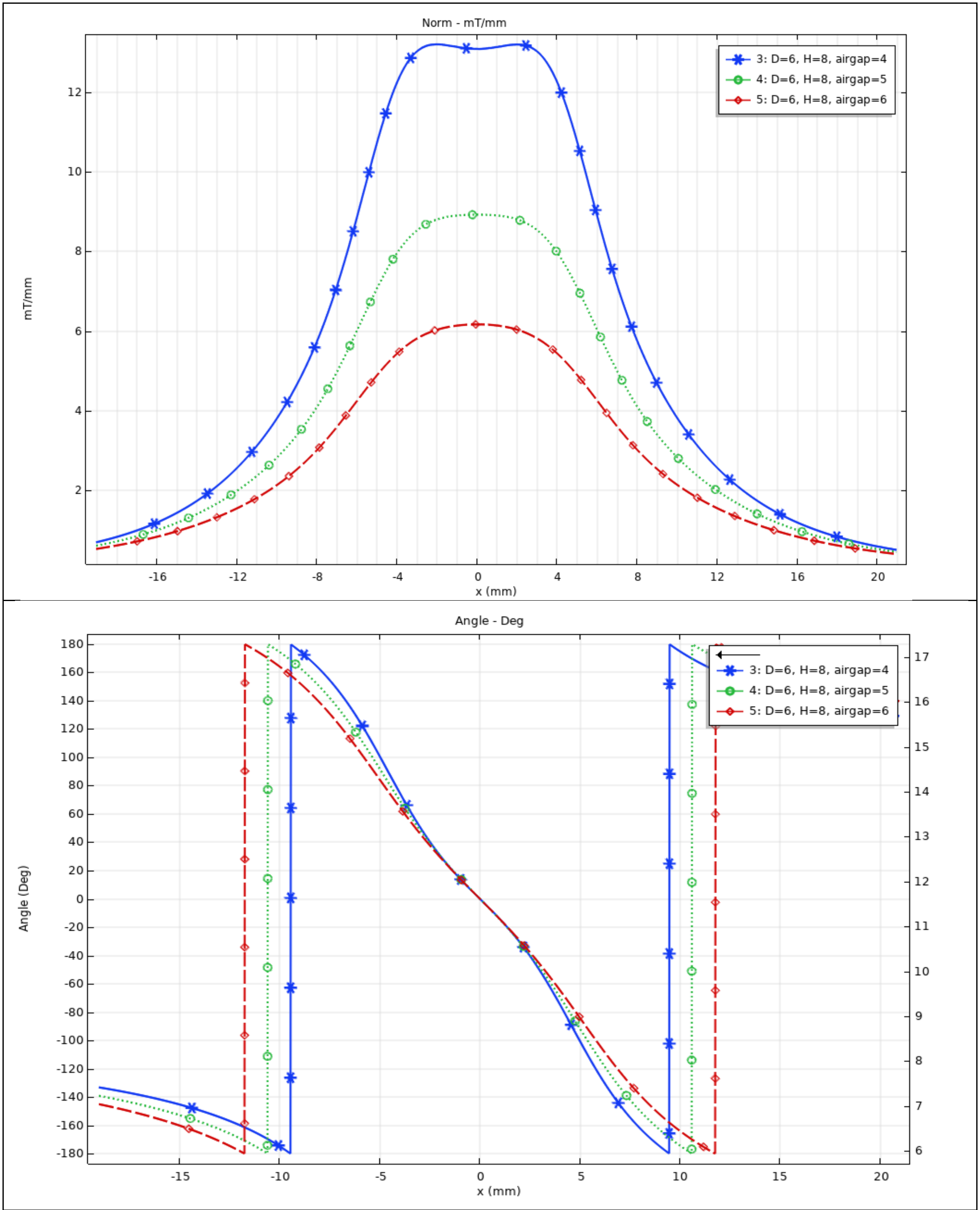
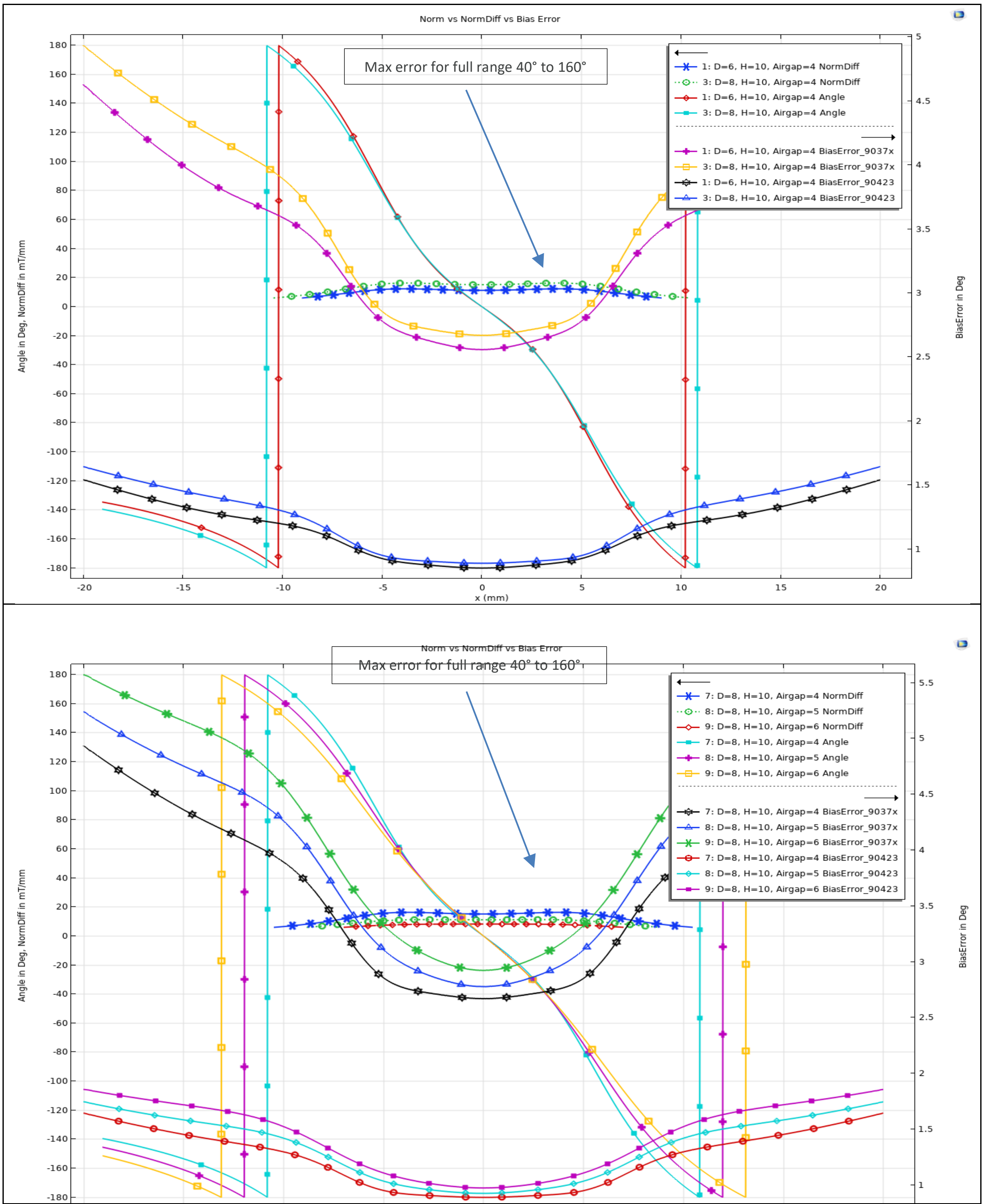
7.2. The effect of air gap variations on the field norm and the sensor output angle



When the air gap (AG) increases, the total gradient field norm decreases, which leads to a decrease in the total relevant stroke and sensor's useful angle range.

Figure 6 The effect of air gap variations on the field norm and the sensor output angle

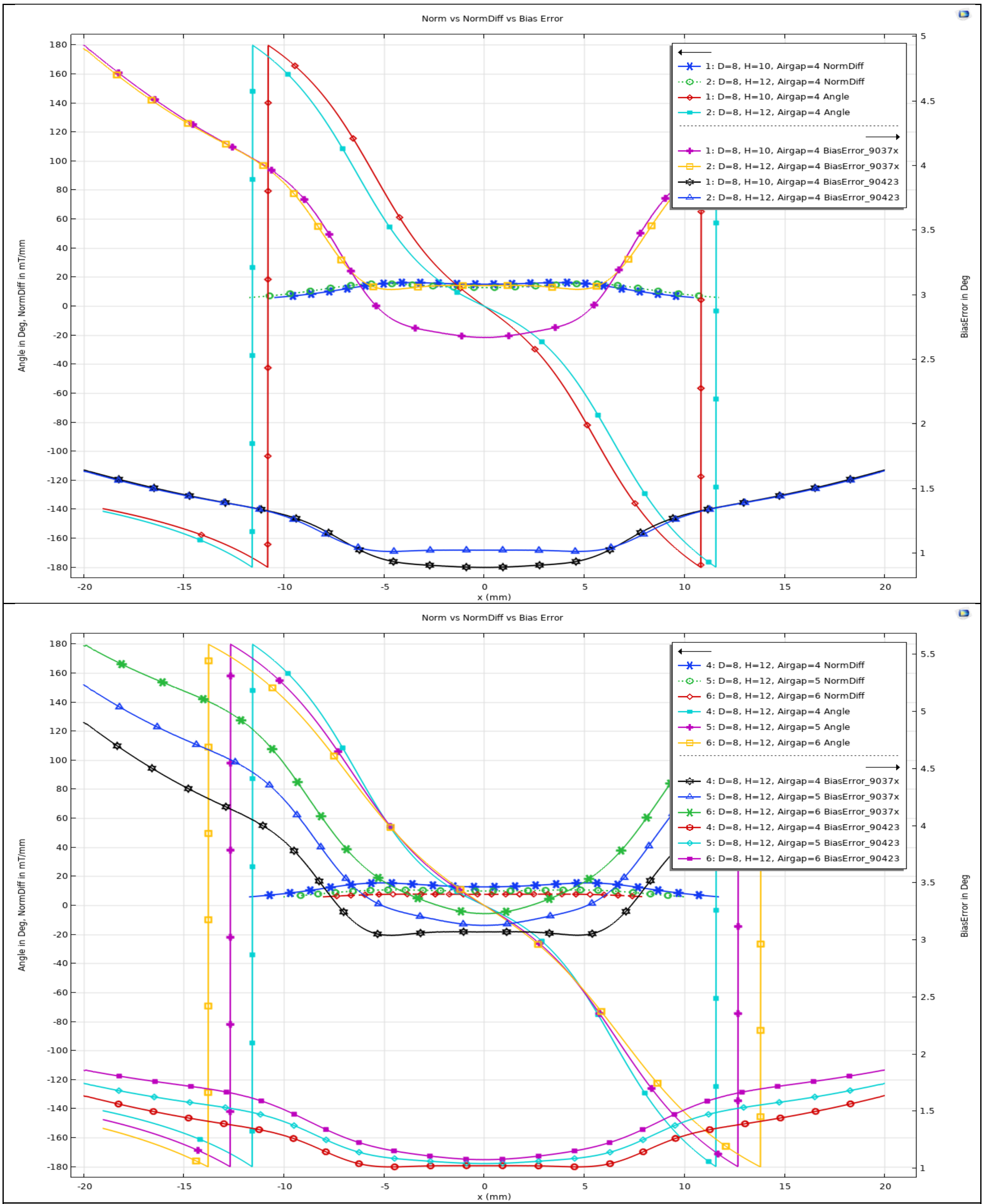
7.3. The effect of magnet dimensions and air gap variations on the thermal bias error



To indicate the relevant stroke area, NormDiff values below 6mT/mm are not shown.

Increasing the diameter **(D)** increases the bias error. The air gap **(AG)** increase, increases the bias error as well. Take note that the relevant %FS (full scale) bias error is dependent on the angle range bounded by the min field norm requirement.

Figure 7 The effect of magnet dimensions on the thermal bias error (MLX9037x) by altering the diameter and air gap.



To indicate the relevant stroke area, NormDiff values below 6mT/mm are not shown.

Increasing the length **(H)** increases the bias error. The air gap **(AG)** increase, increases the bias error as well. Take note that the relevant %FS (full scale) bias error is dependent on the angle range bounded by the min field norm requirement.

Figure 8 The effect of magnet dimensions on the thermal bias error by altering the length and air gap

7.4. Reference designs

Table 8 Magnet reference for two-pole axial parallel designs (Br = 1300mT)

mT/mm	Stroke (±mm)	Stroke (mm)	D (mm)	H (mm)	AG (mm)	α range	Bias error 9037x (%FS)	Bias error 90423 (%FS)
≥6	15	30	10	19	5	348	1.47	0.49
	12	24	10	14	5	334	1.71	0.57
	10	20	10	10	5	314	1.66	0.55
	7	14	10	8	6	232	1.85	0.62
	5	10	10	8	7	148	2.49	0.83
≥3	15	30	10	15	7	338	1.76	0.59
	12	24	8	11	6	340	1.45	0.48
	10	20	8	7	5	352	1.22	0.41
	7	14	8	5	6	264	1.46	0.49
	5	10	10	5	8	158	2.37	0.79

Condition: Field vector Bx <80mT, field vector Bz <100mT

Table 9 Magnet reference for two-pole axial parallel designs (Br = 900mT)

mT/mm	Stroke (±mm)	Stroke (mm)	D (mm)	H (mm)	AG (mm)	α range	Bias error 9037x (%FS)	Bias error 90423 (%FS)
≥6	15	30	12	18	4	360	1.39	0.46
	12	24	12	14	4	346	1.36	0.45
	10	20	12	10	4	326	1.35	0.45
	7	14	10	7	4	290	1.28	0.43
	5	10	8	5	4	250	1.16	0.39
≥3	15	30	12	16	6	350	1.43	0.48
	12	24	12	12	6	332	1.66	0.55
	10	20	10	10	6	300	1.63	0.54
	7	14	8	6	5	295	1.29	0.43
	5	10	6	5	5	240	1.25	0.42

Condition: Field vector Bx <80mT, field vector Bz <100mT

Remark: 360 Degree angle range is in theory not realistic. For best practices, we advise the designer taking a margine into account to safeguard against angle roll-over.

7.5. Conclusion

Table 10 Conclusion behavior for a two-pole axial parallel magnetized magnet

Dimension impact	Gradient field norm		Total relevant stroke		Sensor angle range	
↑ Diameter (D)	••	Increase	•	Increase	•	Increase
↑ Length (H)	•	Increase	•	Increase	•	Increase
↑ Air gap (AG)	•••	Decrease	••	Decrease	••	Decrease

The air gap is the dominant factor when considering the field norm, total stroke, and angle range. When considering the total stroke and angle range, then the diameter and the length have more or less the same effect. The total stoke is roughly two times the magnet’s length.

8. [Case study 2] Two-pole axial orthogonal cylindrical magnet

In a second study, we characterize a standard two-pole axial orthogonal magnet.

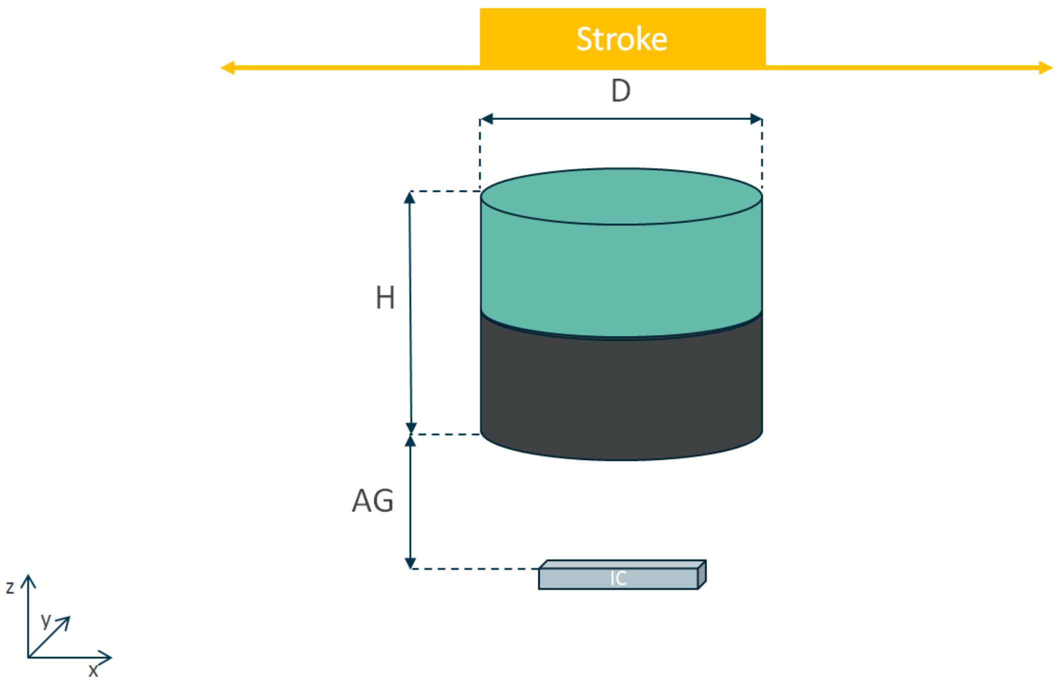


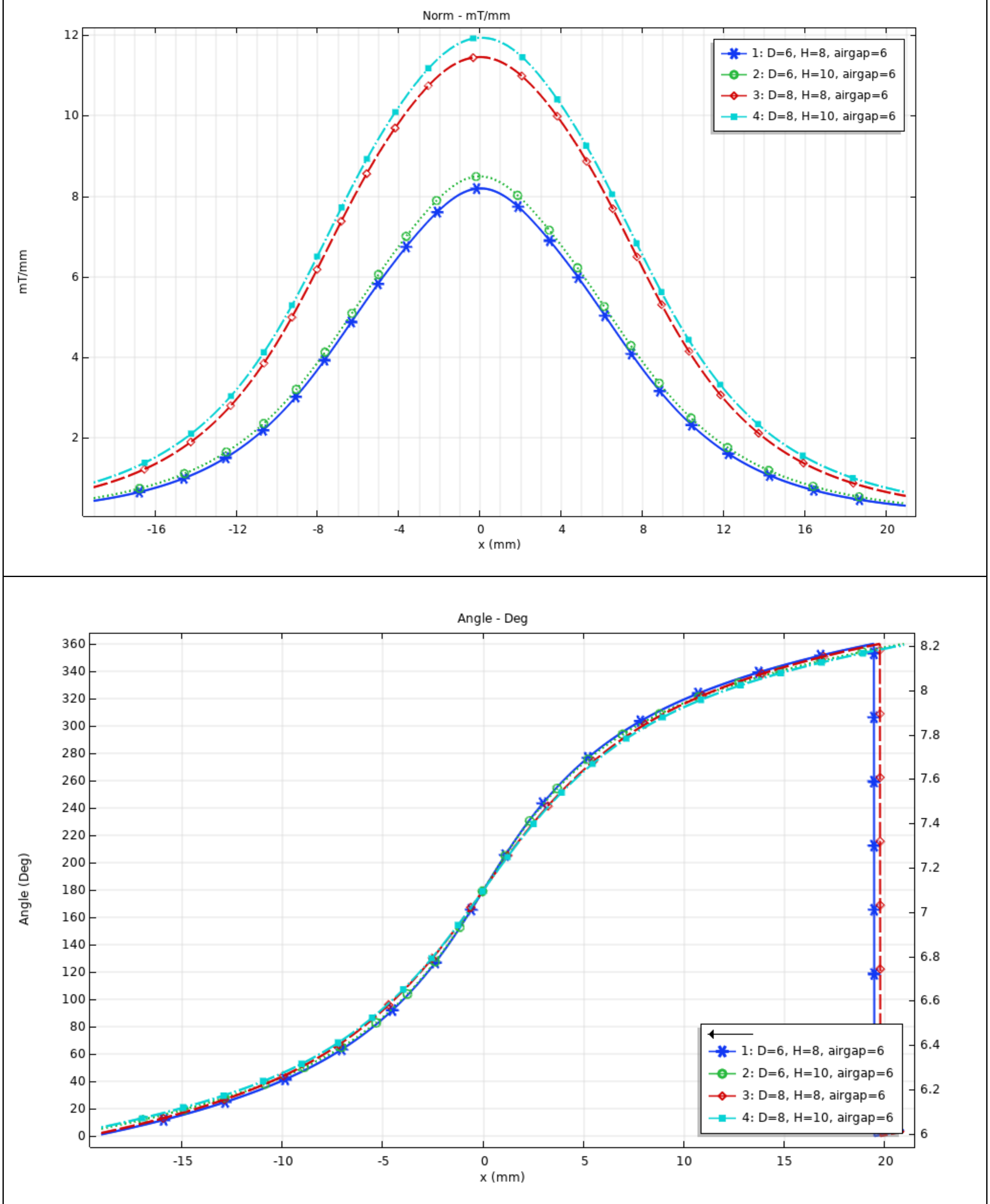
Figure 9 Two-pole axial orthogonal cylindrical magnet

Table 11 Magnet characteristics for a two-pole parallel orthogonal cylindrical magnet

Magnet characteristics base	Value	Remarks
Strength	1300 mT (NdFeB)	
Dimensions	D=6mm / H=8mm	*Ref. magnet selection guide MLX90333*
Magnetization	Axial, along the z-axis	
Environmental conditions	Value	*Remark*
Air gap (AG)	6mm	*Typical simulation air gap*
XY-Tilt	0 Deg	
ZX-Tilt	0 Deg	

Simulation abbreviation:
NormDiff: Magnetic gradient of X-Z Field components

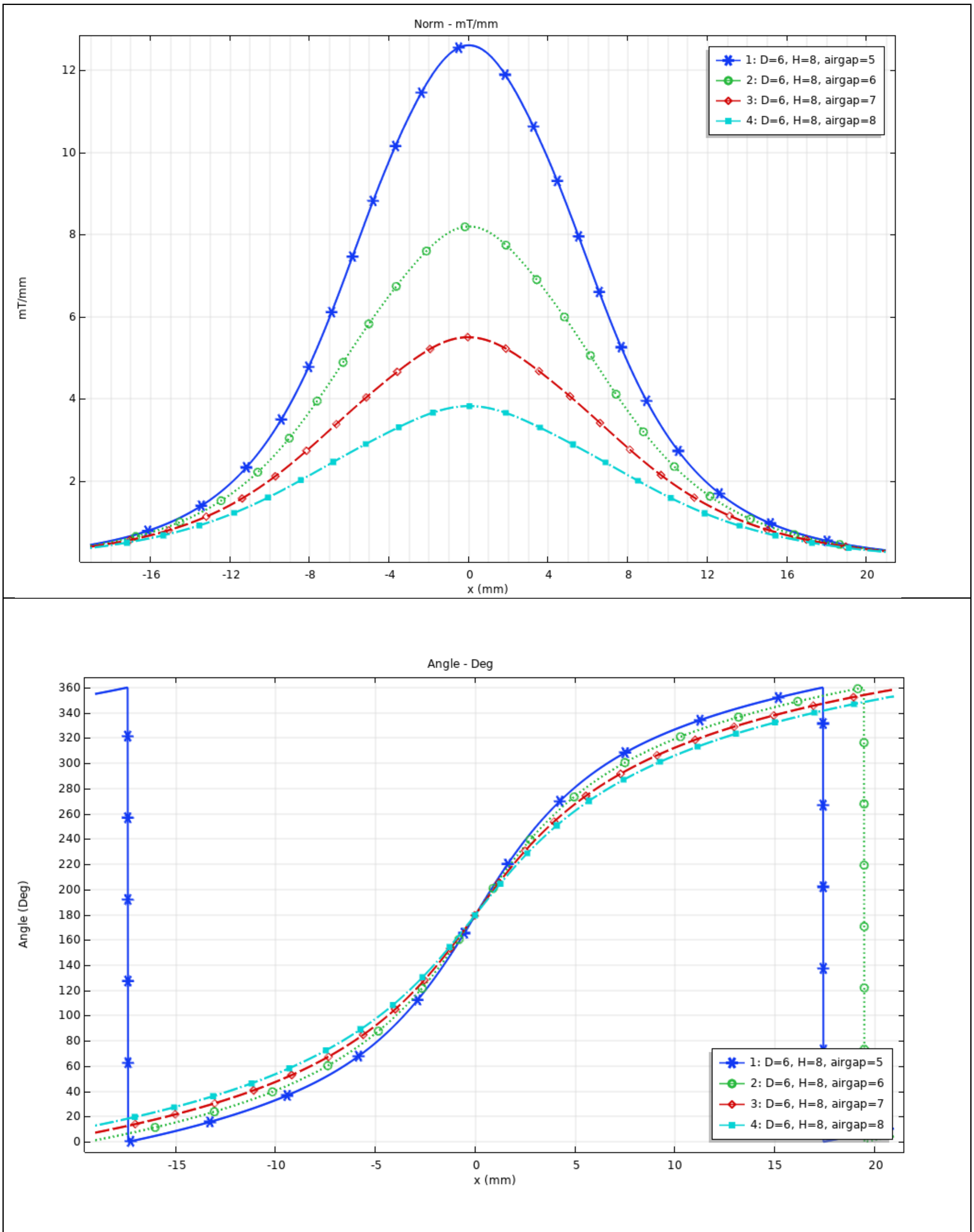
8.1. The effect of magnet dimensions versus the field norm and the sensor output angle



The magnet's diameter **(D)** has a dominant effect on the gradient field norm, while the length **(H)** is contributing less.

Figure 10 The effect of magnet dimensions versus the field norm and the sensor output angle

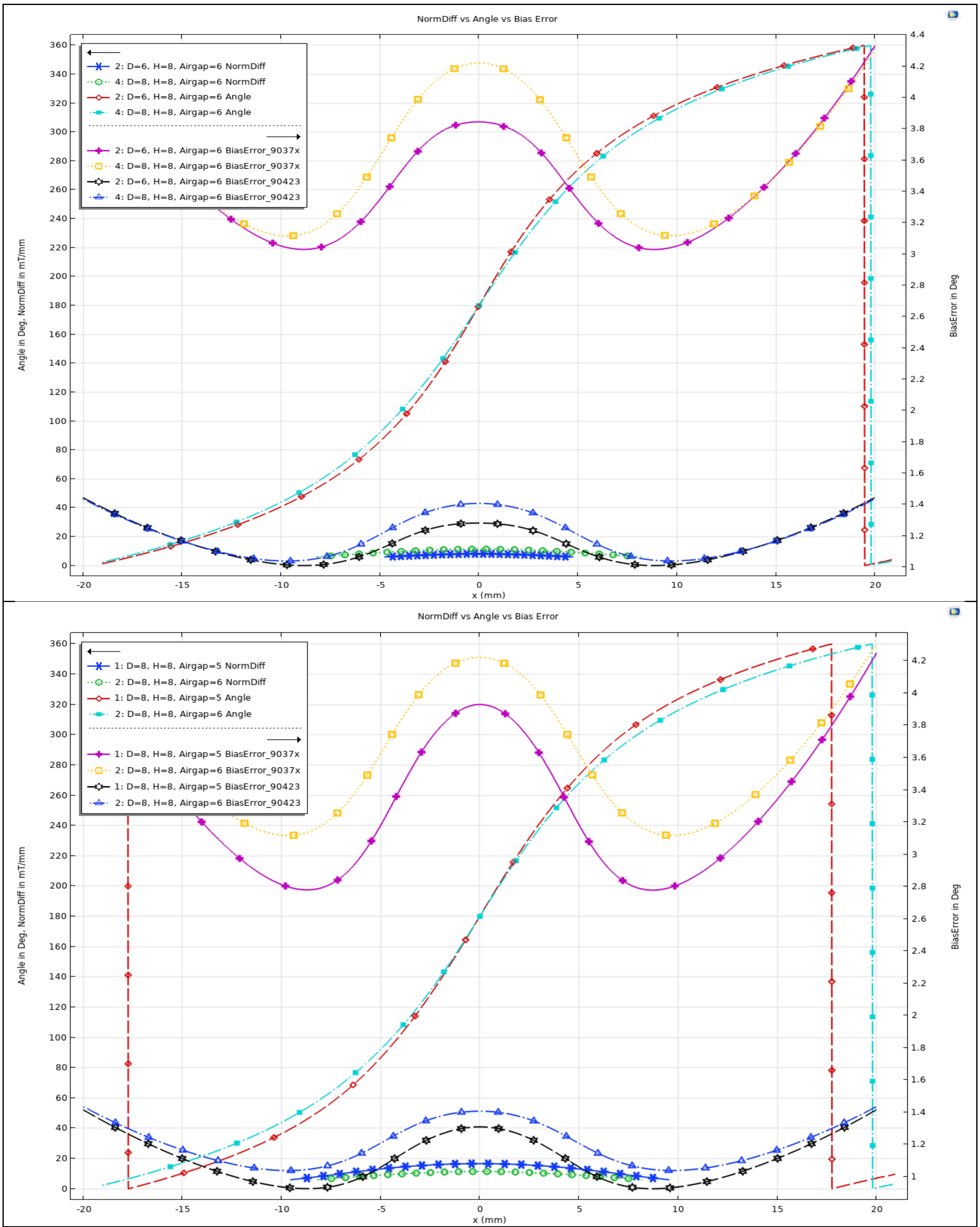
8.2. The effect of air gap variations on the field norm and the sensor output angle



The air gap (AG) has a dominant effect on the total gradient field norm. The increasing air gap leads to a decrease in the total relevant stroke and sensor's useful angle range.

Figure 11 The effect of air gap variations on the field norm and the sensor output angle

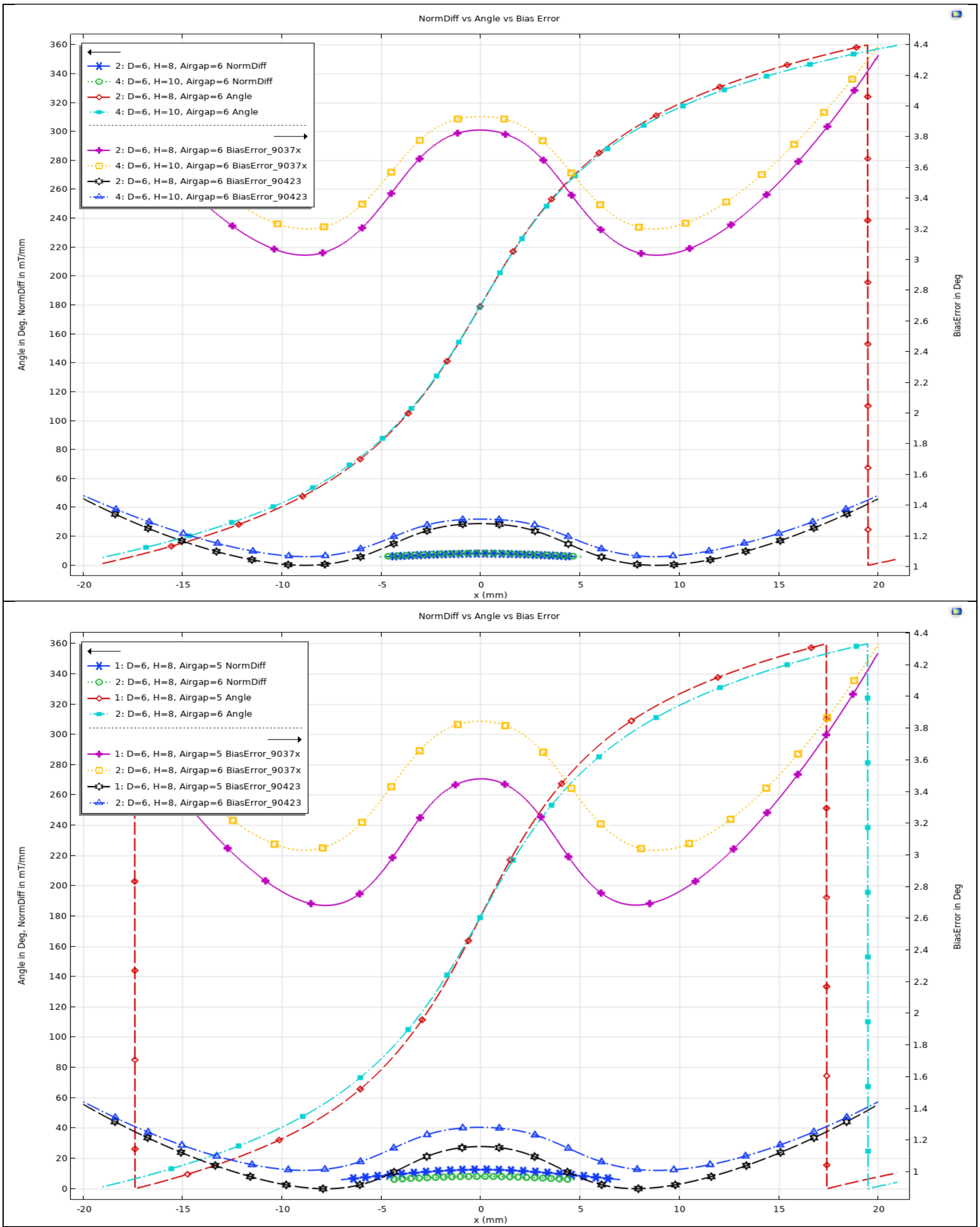
8.3. The effect of magnet dimensions and air gap variations on the thermal bias error



To indicate the relevant stroke area, NormDiff values below 6mT/mm are not shown.

Increasing the diameter **(D)** and the air gap **(AG)** increase the bias error. Take note that the relevant %FS bias error is dependent on the angle range bounded by the min field norm requirement.

Figure 12 The effect of magnet dimensions on the thermal bias error by altering the diameter and air gap



To indicate the relevant stroke area, NormDiff values below 6mT/mm are not shown.

Increasing the length **(H)** and air gap **(AG)** increase the bias error. Take note that the relevant %FS bias error is dependent on the angle range bounded by the min field norm requirement.

Figure 13 The effect of magnet dimensions on the thermal bias error by altering the length and air gap

8.4. Reference designs

Table 12 Magnet reference for two-pole axial orthogonal designs (1300mT)

mT/mm	Stroke (±mm)	Stroke (mm)	D (mm)	H (mm)	AG (mm)	α range	Bias error 9037x (%FS)	Bias error 90423 (%FS)
≥6	15	30	20	4	7	282	2.70	0.90
	12	24	17	5	8	243	2.78	0.93
	10	20	10	6	6	270	1.70	0.57
	7	14	5	10	4	268	1.12	0.37
	5	10	5	7	5	216	2.66	0.89
≥3	15	30	14	4	7	314	1.85	0.62
	12	24	8	9	6	296	1.45	0.48
	10	20	6	5	4	325	0.92	0.31
	7	14	6	7	7	226	1.84	0.61
	5	10	5	9	7	182	2.34	0.78

Condition: Field vector Bx <80mT, field vector Bz <100mT

Table 13 Magnet reference for two-pole axial orthogonal designs (900mT)

mT/mm	Stroke (±mm)	Stroke (mm)	D (mm)	H (mm)	AG (mm)	α range	Bias error 9037x (%FS)	Bias error 90423 (%FS)
≥6	15	30	20	4	5	292	2.84	0.95
	12	24	16	4	5	280	2.29	0.76
	10	20	12	5	5	266	1.88	0.63
	7	14	8	3	4	260	1.31	0.44
	5	10	6	3	4	230	1.22	0.41
≥3	15	30	14	5	5	322	1.77	0.59
	12	24	10	5	5	300	1.47	0.49
	10	20	8	5	5	284	1.34	0.45
	7	14	6	4	5	240	1.33	0.44
	5	10	5	3	5	210	1.38	0.46

Condition: Field vector Bx <80mT, field vector Bz <100mT

8.5. Conclusion

Table 14 Conclusion behavior for a two-pole axial orthogonal magnetized magnet

Dimension impact	Gradient field norm		Total relevant stroke		Sensor angle range	
↑ Diameter (D)	••	Increase	•••	Increase	••	Increase
↑ Length (H)	•	Decrease	•	Increase	•	Decrease
↑ Air gap (AG)	•••	Decrease	••	Decrease	•••	Decrease

The air gap is the dominant factor when considering the field norm and angle range. When considering the total stroke, the diameter is dominant. The length is contributing the least. The design for the orthogonal model is more critical on volume than the parallel model as the diameter is the highest contributor. The total stoke is roughly two times the magnet's diameter.

9. [Case study 3] Three pole axial (sinusoidal) parallel cylindrical magnet

In a third study, we characterize a three-pole (sinusoidal) parallel cylindrical magnet.

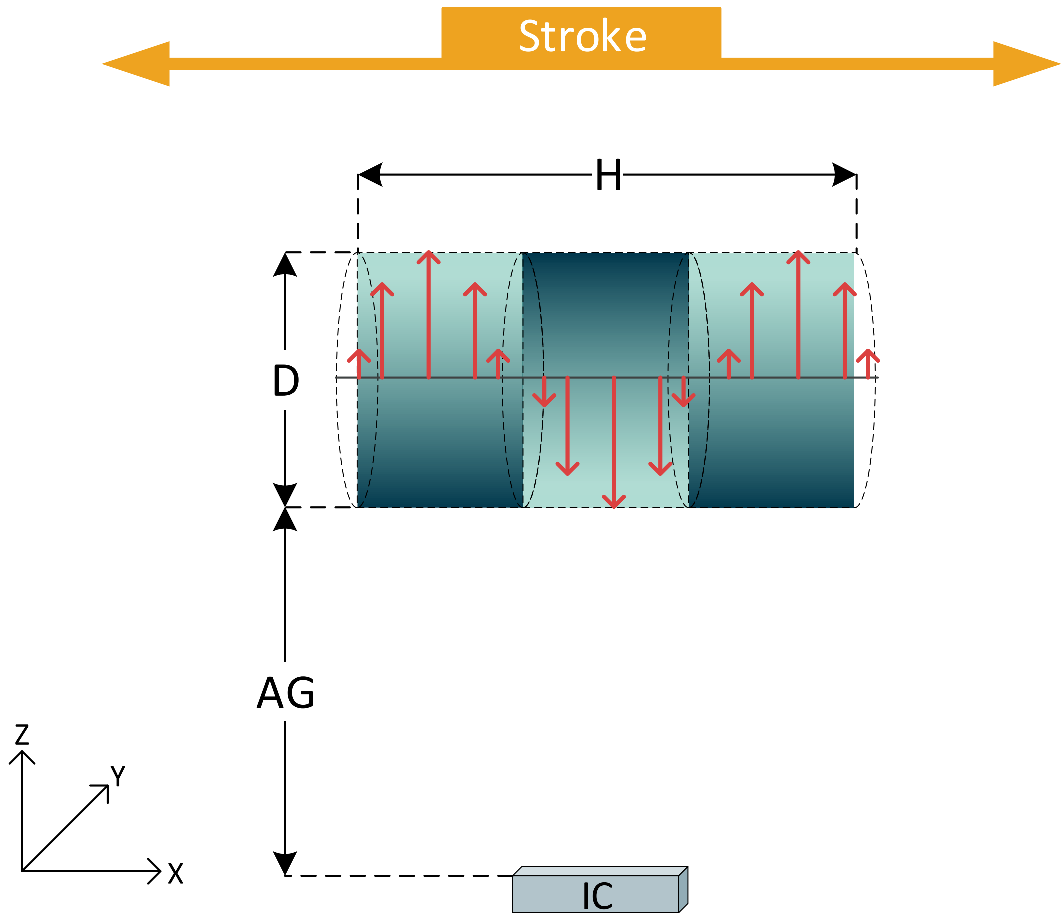


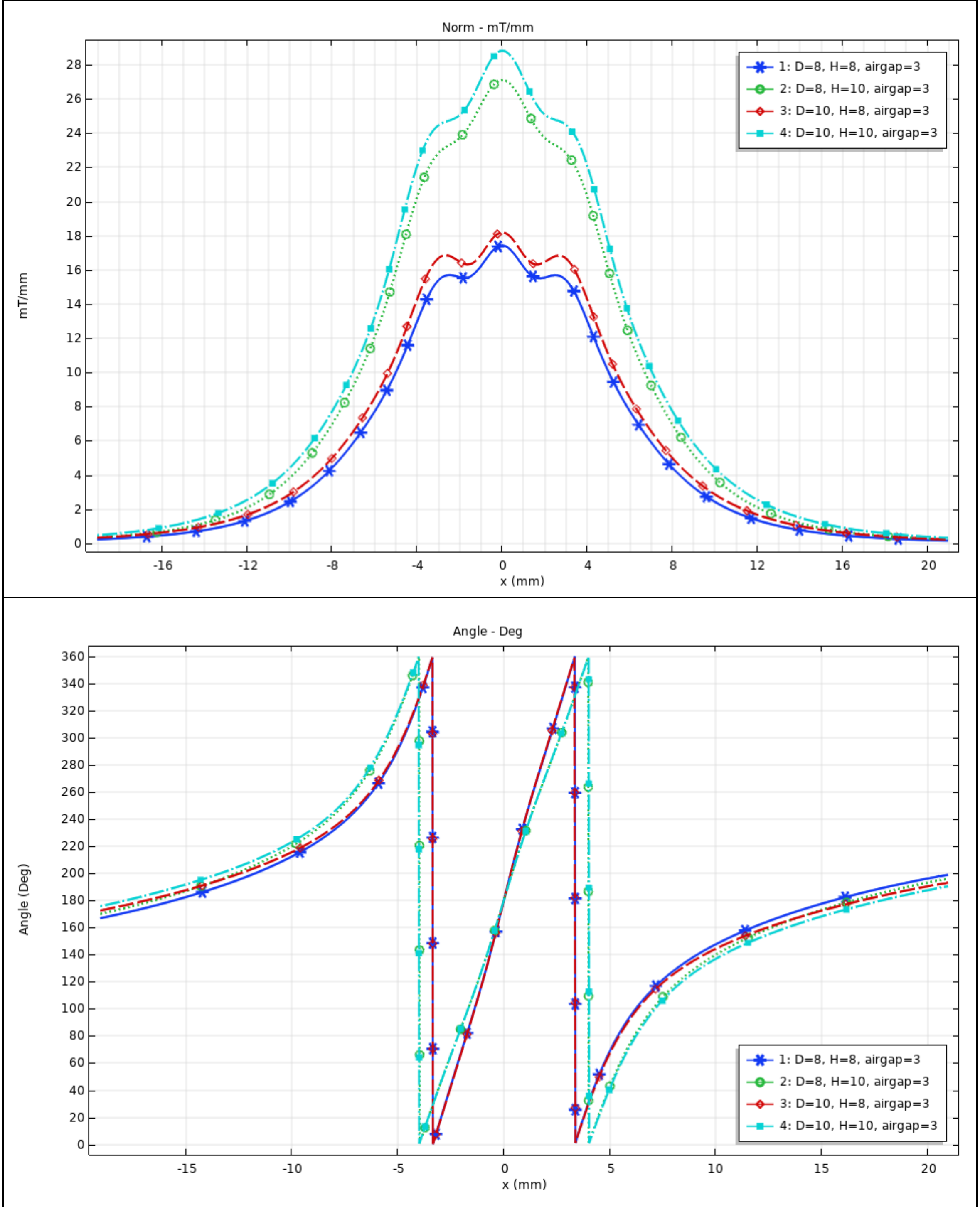
Figure 14 Three pole axial (sinusoidal) parallel cylindrical magnet

Table 15 Magnet characteristics for a three-pole axial (sinusoidal) parallel cylindrical magnet

Magnet characteristics base	Value	Remarks
Strength	1300 mT (NdFeB)	
Dimensions	D=6mm / H=8mm	
Magnetization	Axial sinusoidal, along the z-axis	
Environmental conditions	**Value**	***Remark***
Air gap (AG)	3mm	*Typical simulation air gap*
XY-Tilt	0 Deg	
ZX Tilt	0 Deg	

Simulation abbreviation:
NormDiff: Magnetic gradient of X-Z Field components

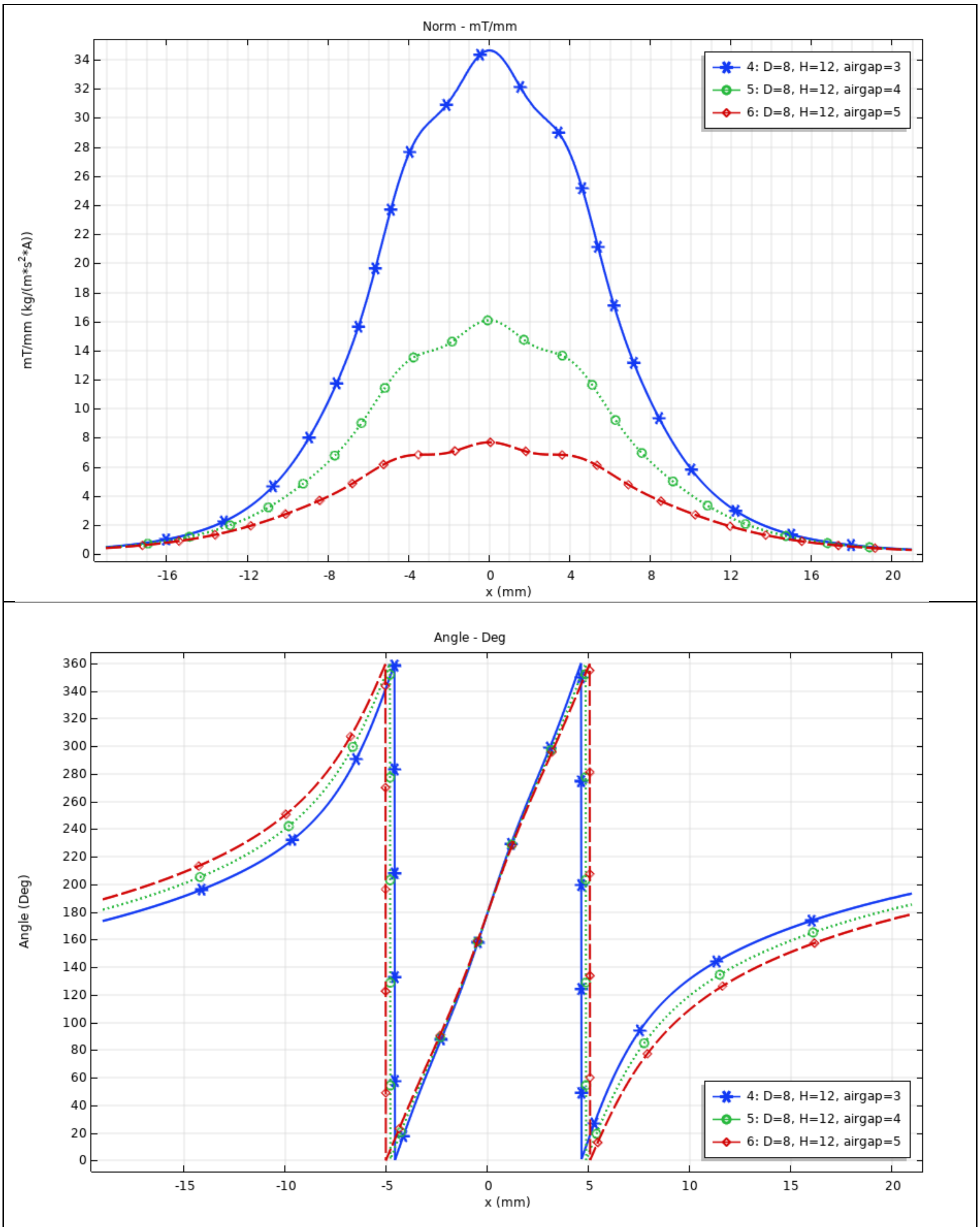
9.1. The effect of magnet dimensions versus the field norm and the sensor output angle



The magnet's length **(H)** has a dominant effect on the gradient field norm, while the diameter **(D)** is contributing less. Increasing the length increases the total relevant stroke.

Figure 15 The effect of magnet dimensions versus the field norm and the sensor output angle

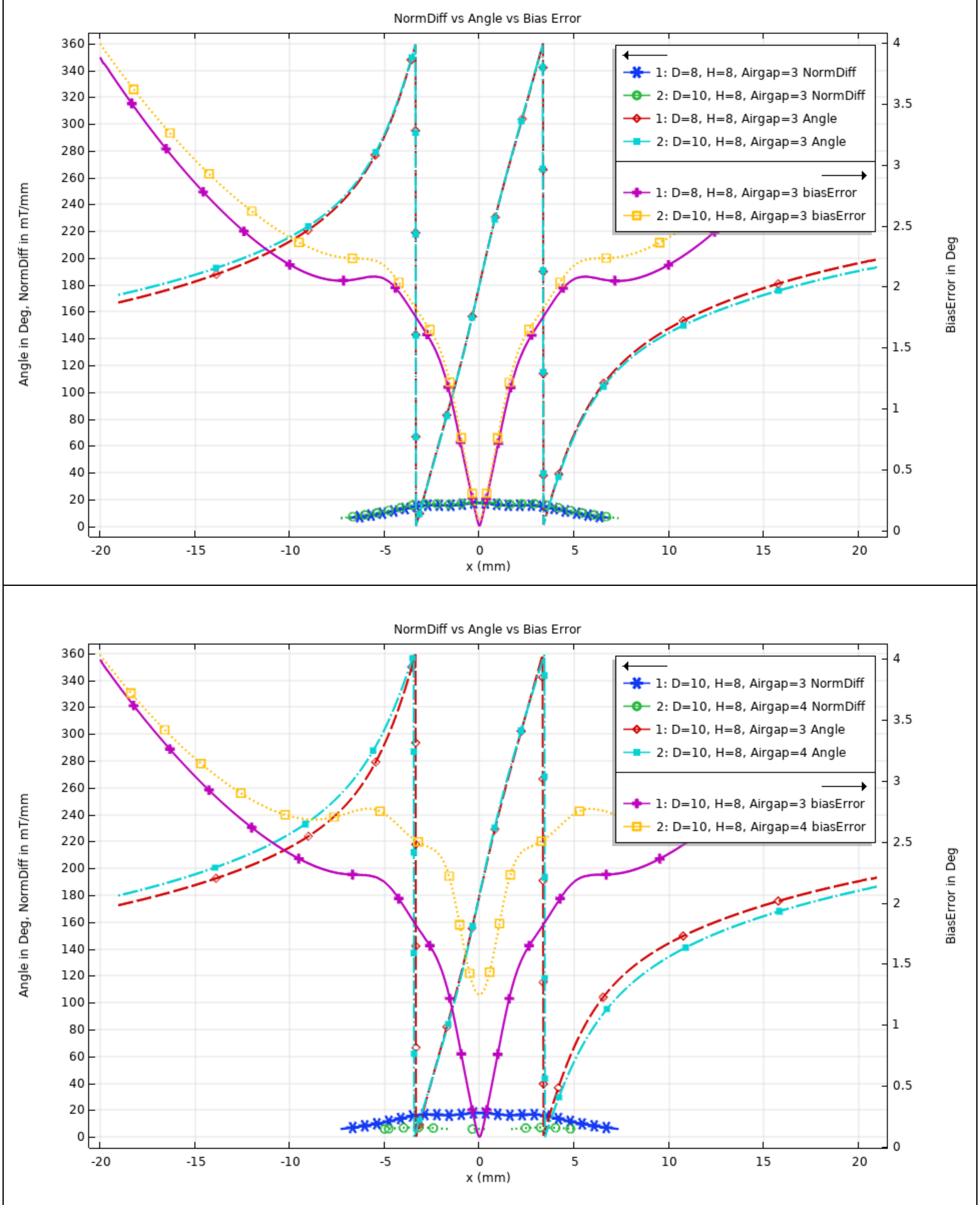
9.2. The effect of air gap variations on the field norm and the sensor output angle



When the air gap **(AG)** increases, the total gradient field norm decreases, which leads to a small increase in the total relevant stroke.

Figure 16 The effect of air gap variations on the field norm and the sensor output angle

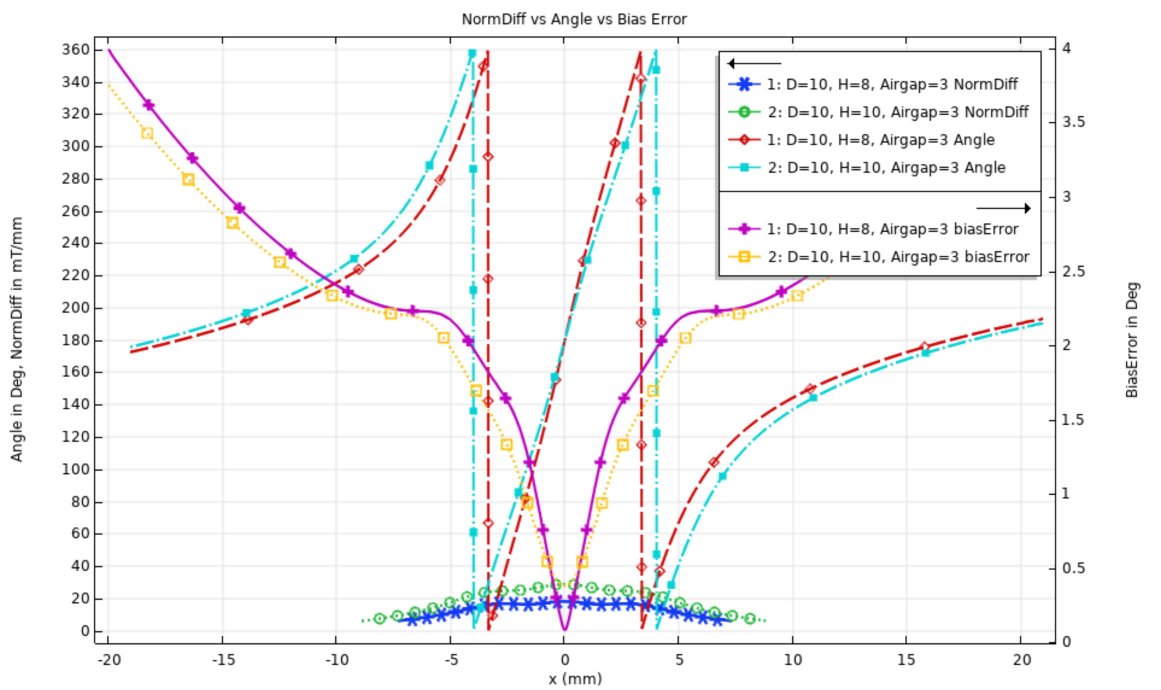
9.3. The effect of magnet dimensions and air gap variations on the thermal bias error

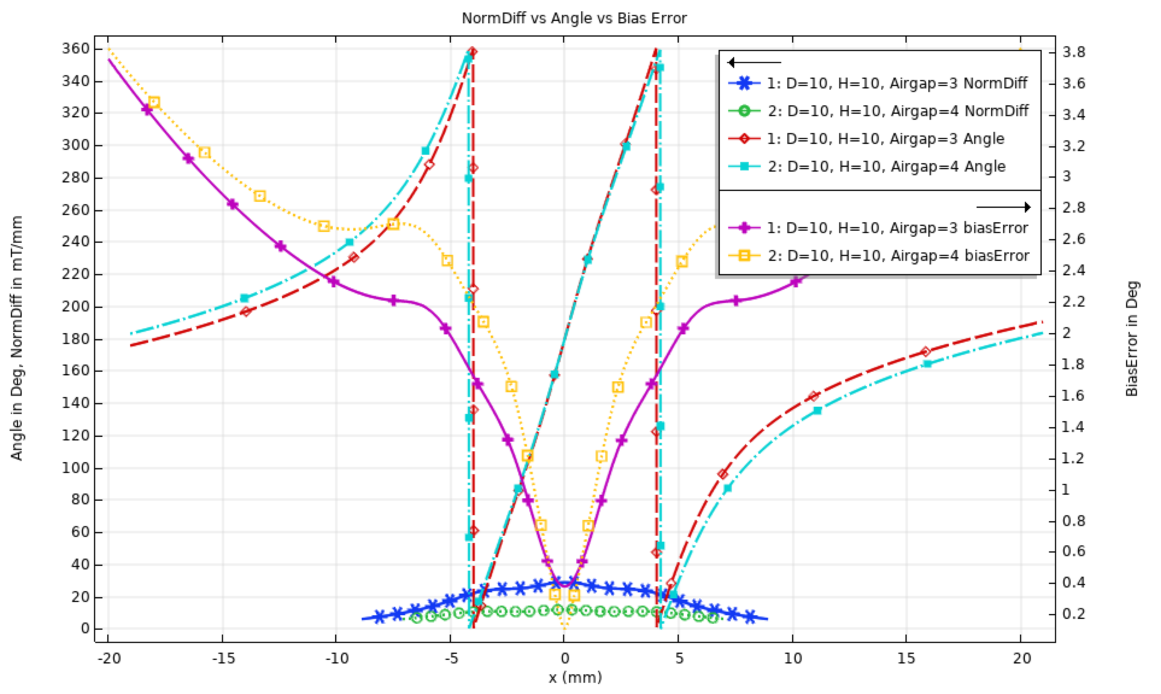


To indicate the relevant stroke area, NormDiff values below 6mT/mm are not shown.

Increasing the diameter **(D)** has a neglectable impact on the bias error (considering the relevant angle range). Increasing the air gap **(AG)** increases the bias error significantly.

Figure 17 The effect of magnet dimensions on the thermal bias error(9037x) by altering the diameter and air gap





To indicate the relevant stroke area, NormDiff values below 6mT/mm are not shown.

Increasing the length **(H)** slightly lowers the bias error (considering the relevant angle range). Increasing the air gap **(AG)** increases the bias error slightly.

Figure 18 The effect of magnet dimensions on the thermal bias error (9037x)by altering the length and air gap

9.4. Reference designs

Table 16 Magnet reference for thee pole axial (sinusoidal) parallel magnet designs (1300mT)

mT/mm	Stroke (±mm)	Stroke (mm)	D (mm)	H (mm)	AG (mm)	α range	Bias error 9037x (%FS)	Bias error 90423 (%FS)
≥6	15	30	8	45	6	350	1.29	0.43
	12	24	8	35	6	350	1.04	0.35
	10	20	8	30	5	340	0.90	0.30
	7	14	8	20	5	335	0.72	0.24
	5	10	8	12	5	360	0.69	0.23
≥3	15	30	4	45	6	355	1.31	0.44
	12	24	4	35	6	360	1.01	0.34
	10	20	4	30	6	340	0.92	0.31
	7	14	4	20	6	330	0.74	0.25
	5	10	4	15	4	315	0.57	0.19

Condition: Field vector Bx <80mT, field vector Bz <100mT

Table 17 Magnet reference for thee pole axial (sinusoidal) parallel magnet designs (900mT)

mT/mm	Stroke (±mm)	Stroke (mm)	D (mm)	H (mm)	AG (mm)	α range	Bias error 9037x (%FS)	Bias error 90423 (%FS)
≥6	15	30	8	45	6	350	1.29	0.43
	12	24	8	35	6	350	1.04	0.35
	10	20	8	30	6	330	0.95	0.32
	7	14	8	20	5	330	0.73	0.24
	5	10	8	15	4	310	0.61	0.20
≥3	15	30	4	45	5	355	1.34	0.45
	12	24	4	35	6	360	1.01	0.34
	10	20	4	30	6	340	0.92	0.31
	7	14	4	20	5	340	0.69	0.23
	5	10	4	15	5	300	0.63	0.21

Condition: Field vector Bx <80mT, field vector Bz <100mT

9.5. Conclusion

Table 18 Conclusion behavior for a three-pole axial (sinusoidal) parallel magnetized magnet

Dimension impact	Gradient field norm		Total relevant stroke		Sensor angle range	
↑ Diameter (D)	•	Increase	•	Increase	•	Decrease
↑ Length (H)	••	Decrease	•••••	Increase	•••	Decrease
↑ Air gap (AG)	•••	Decrease	•	Increase	•	Decrease

The airgap (AG) has a dominant impact on the gradient field norm. The Length (H) has a dominant effect on the total stroke length, which is roughly 1.5 times the length of the total stroke. The diameter (D) and airgap (AG) has a minor impact on the stroke length. This same conclusion applies to the sensor's angle range. The total stroke is ~ magnet's Length/1.5.

10. [Case study 4] Three-pole axial parallel cylindrical magnet

In a fourth study, we characterize a three-pole parallel cylindrical magnet.

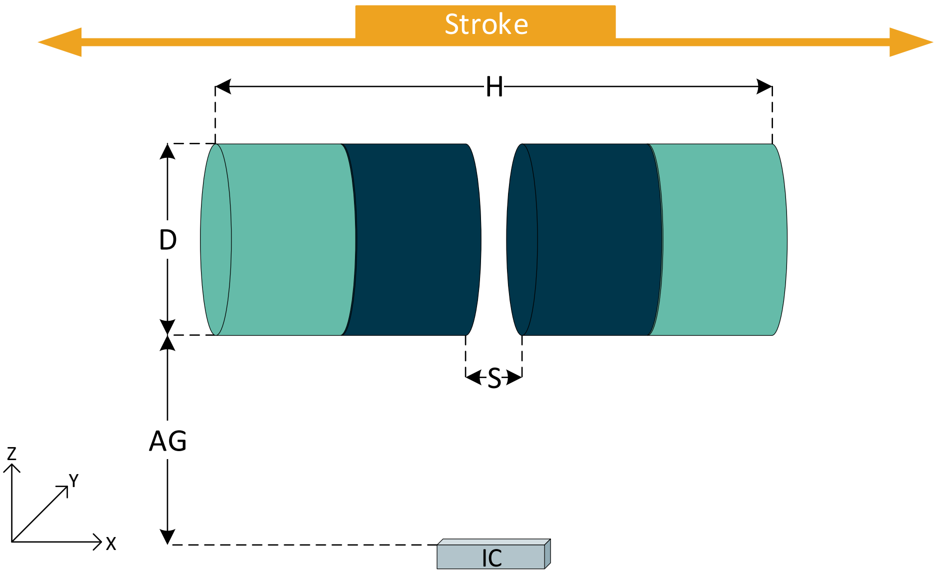


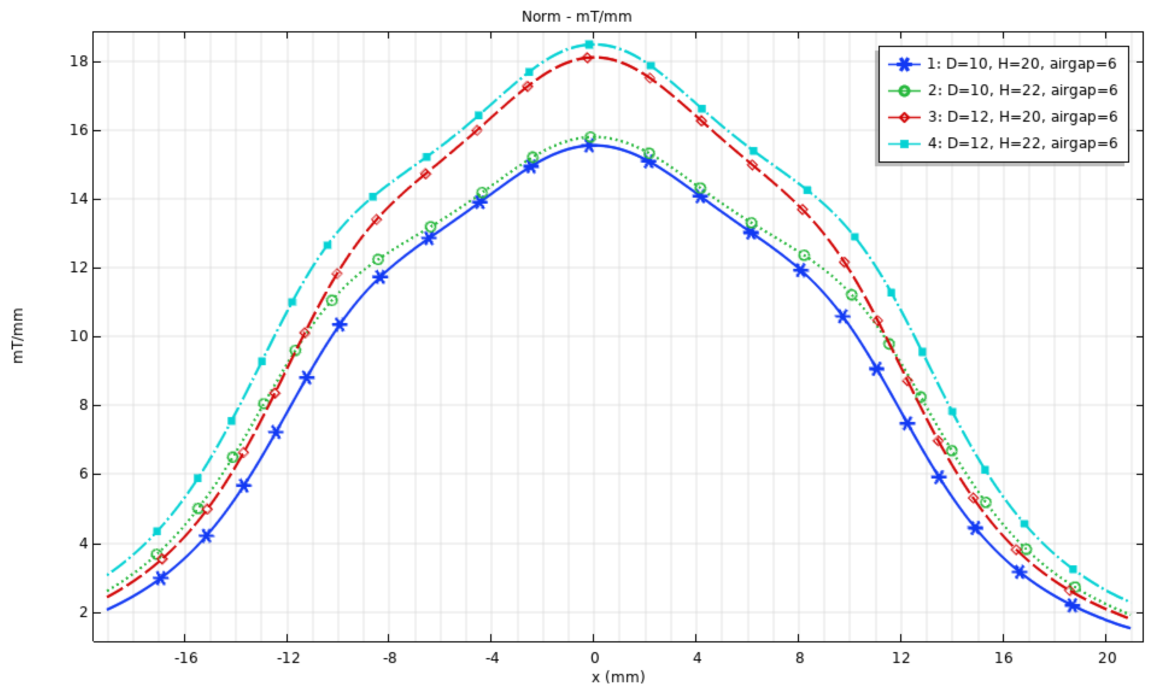
Figure 19 Three pole axial parallel cylindrical magnet

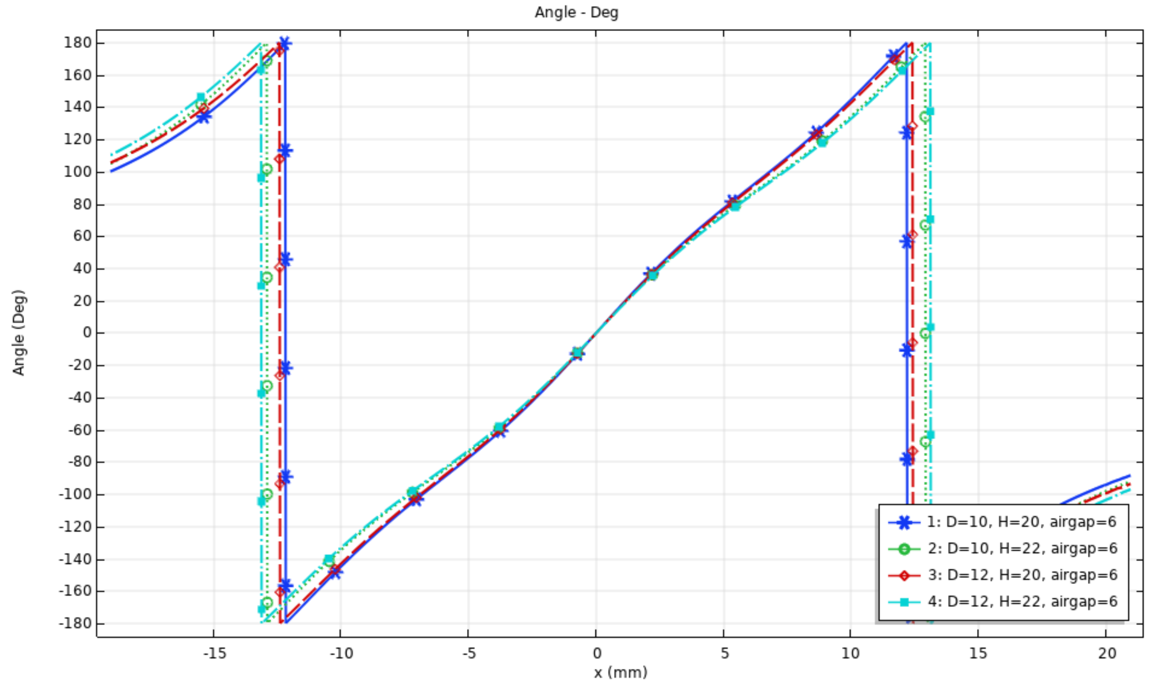
Table 19 Magnet characteristics for a three-pole axial parallel cylindrical magnet

Magnet characteristics base	Value	Remarks
Strength	1300 mT (NdFeB)	
Dimensions	D=6mm / H=8mm	
Magnetization	Axial, along the x-axis	
Environmental conditions	Value	*Remark*
Air gap (AG)	6mm	*Typical simulation air gap*
Space (S)	3mm	
XY-Tilt	0 Deg	
ZX Tilt	0 Deg	

Simulation abbreviation:
NormDiff: Magnetic gradient of X-Z Field components

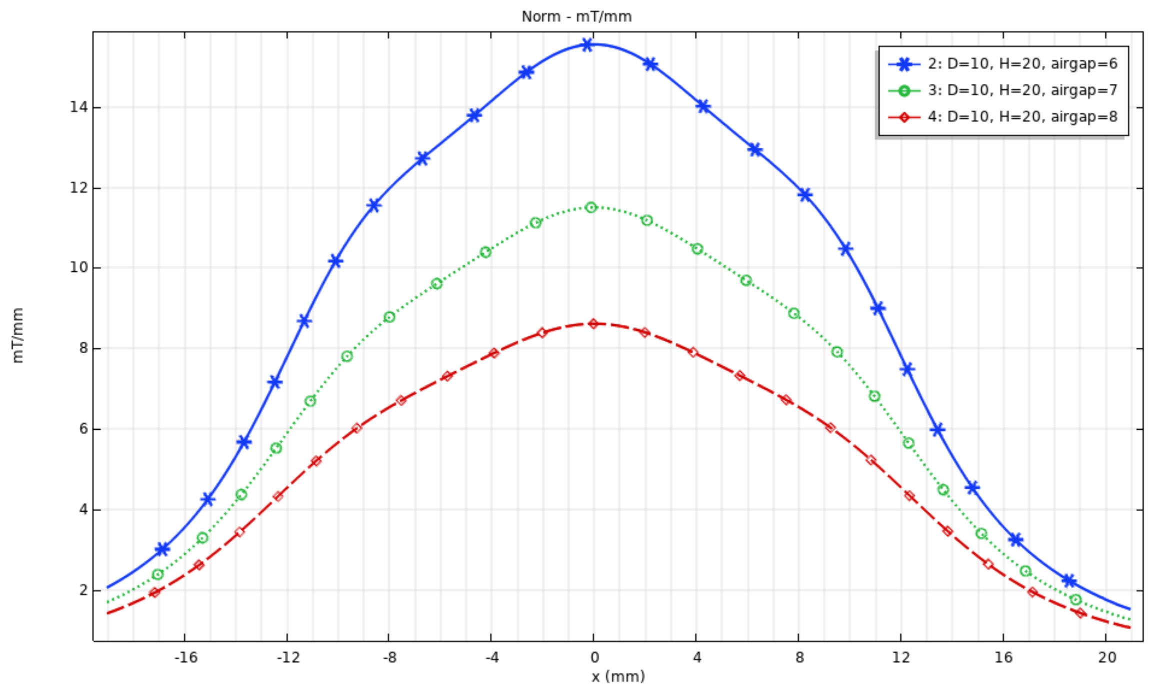
10.1. The effect of magnet dimensions versus the field norm and the sensor output angle

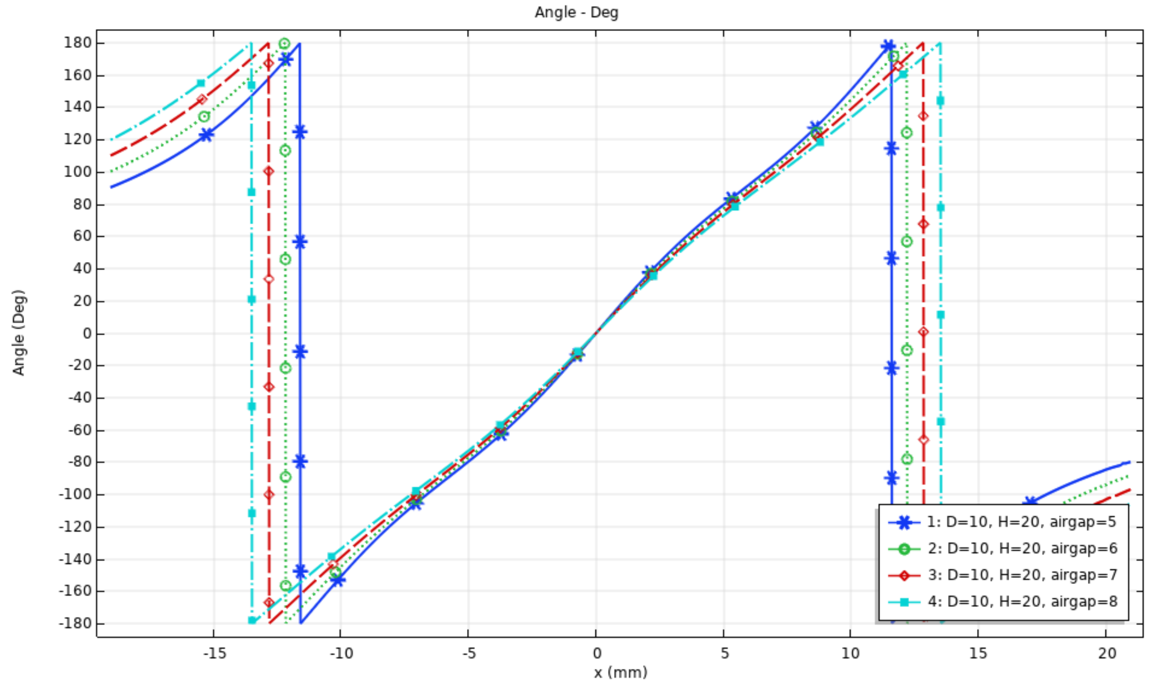




The magnet's diameter **(D)** has a dominant effect on the gradient field norm, while the length **(H)** is contributing less. Increasing the length increases the total relevant stroke.

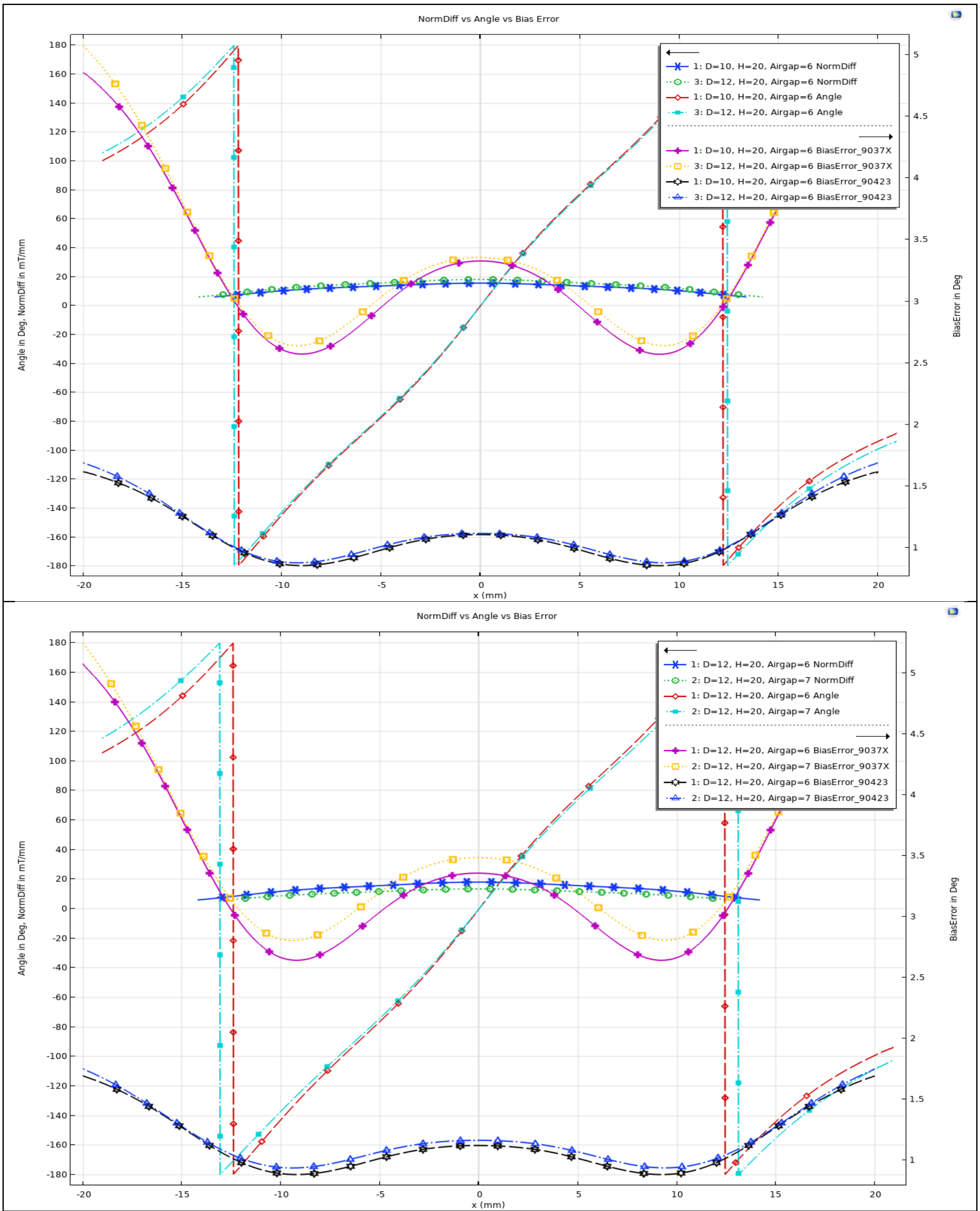
10.2. The effect of air gap variations on the field norm and the sensor output angle





When the air gap **(AG)** increases, the total gradient field norm decreases, which leads to a small increase in the total relevant stroke.

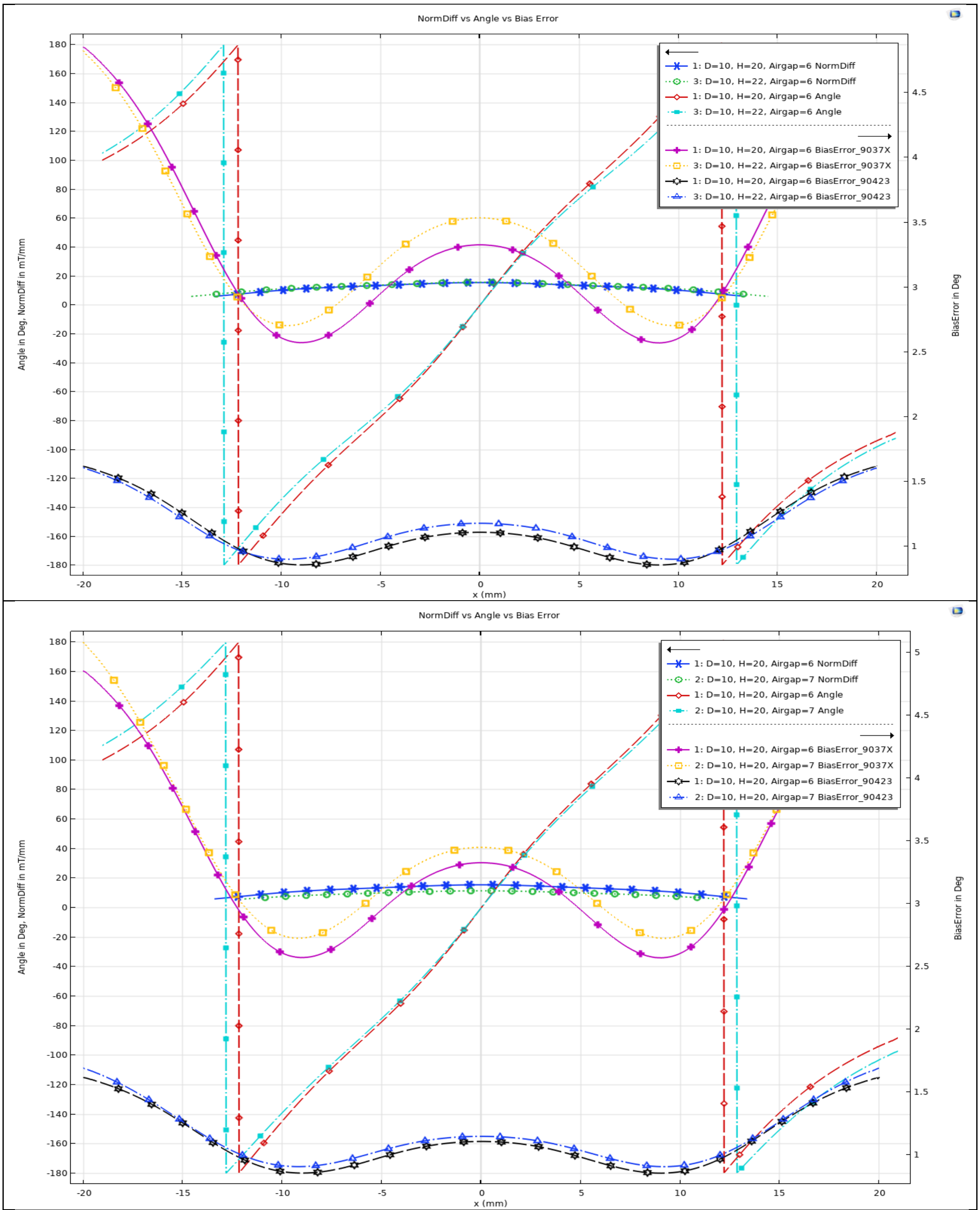
10.3. The effect of magnet dimensions and air gap variations on the thermal bias error



To indicate the relevant stroke area, NormDiff values below 6mT/mm are not shown.

Increasing the diameter **(D)** has a neglectable impact on the bias error (considering the relevant angle range). Increasing the air gap **(AG)** increases the bias error slightly.

Figure 20 The effect of magnet dimensions on the thermal bias error by altering the diameter and air gap



To indicate the relevant stroke area, NormDiff values below 6mT/mm are not shown.

Increasing the length **(H)** increases the bias error (considering the relevant angle range). Increasing the air gap **(AG)** increases the bias error.

Figure 21 The effect of magnet dimensions on the thermal bias error by altering the length and air gap

10.4. Reference designs

Table 20 Magnet reference for thee pole axial parallel magnet designs (1300mT)

mT/mm	Stroke (±mm)	Stroke (mm)	D (mm)	H (mm)	S (mm)	AG (mm)	α range	Bias error 9037x (%FS)	Bias error 90423 (%FS)
≥6	15	30	8	30	1..3	6	330	1.27	**0.42**
	12	24	10	20		6	355	0.94	**0.31**
	10	20	10	15		6	345	0.81	**0.27**
	7	14	8	10		4	350	0.57	**0.19**
	5	10	4	8		3	330	0.52	**0.17**
≥3	15	30	4	30	1..3	4	355	1.06	**0.35**
	12	24	6	20		7	355	0.96	**0.32**
	10	20	8	15		6	355	0.79	**0.26**
	7	14	4	12		4	340	0.65	**0.22**
	5	10	4	8		3	325	0.51	**0.17**

Condition: Field vector Bx <80mT, field vector Bz <100mT

Table 21 Magnet reference for thee pole axial parallel magnet designs (900mT)

mT/mm	Stroke (±mm)	Stroke (mm)	D (mm)	H (mm)	S (mm)	AG (mm)	α range	Bias error 9037x (%FS)	Bias error 90423 (%FS)
≥6	15	30	8	30	1..3	5	340	1.19	0.40
	12	24	6	25		5	310	1.18	0.39
	10	20	6	20		5	310	1.02	0.34
	7	14	8	10		4	345	0.58	0.19
	5	10	6	8		3	330	0.50	0.17
≥3	15	30	4	30	1..3	4	355	1.06	0.35
	12	24	4	25		4	320	1.08	0.36
	10	20	4	20		4	330	0.92	0.31
	7	14	4	12		4	340	0.65	0.22
	5	10	4	8		3	330	0.50	0.17

Condition: Field vector Bx <80mT, field vector Bz <100mT

10.5. Conclusion

Table 22 Conclusion behavior for a three-pole axial parallel magnetized magnet

Dimension impact	Gradient field norm		Total relevant stroke		Sensor angle range	
↑ Diameter (D)	•	Increase	•	Increase	•	Decrease
↑ Length (H)	••	Increase	•••••	Increase	•••	Decrease
↑ Air gap (AG)	•••	Decrease	•	Increase	•	Decrease
↑ Space (S)	••	Decrease		-		-

The trends of the diameter **(D)** length **(H)** and airgap **(AG)** is very similar to the three-pole sinusoidal magnet. Also, the length requirement of the magnet is ~1:1 to the length of the total stroke instead of ~1.5:1 relation for the sinusoidal magnetized magnet. What's more, the space **(S)** between two magnets has an impact on the Bz-field, gradient-field, and bias error only in the center area of the total stroke. There is no apparent impact on the stroke length and angle range. The total stroke is ~ magnet's length.

11. General conclusion

Two pole magnets are commonly used and are typically easy to assemble. If we considering the %FS bias error, we find that two-pole parallel cylindrical magnets are preferable as apposed to orthogonal cylindrical magnets. However, on that same note, we find the best performance with three-pole magnets, and when we look at three-pole magnets, two practical points emerge; First, sinusoidal magnetized magnets might be difficult to magnetize. Second, depending on the design, the three-pole magnet might be more challenging to assemble. Below we list again the essential characteristics per magnet apart from the reference design. To minimize the effect of the bias error and get the best performance , we recommend to use the MLX90423.

Two-pole axial parallel cylindrical magnet - (total stroke is roughly two times the magnet's length)

Dimension impact	Gradient field norm		Total relevant stroke		Sensor angle range	
↑ Diameter (D)	••	Increase	•	Increase	•	Increase
↑ Length (H)	•	Increase	•	Increase	•	Increase
↑ Air gap (AG)	•••	Decrease	••	Decrease	••	Decrease

The air gap is the dominant factor when considering the field norm, total stroke, and angle range. When considering the total stroke and angle range, then the diameter and the length have more or less the same effect.

Two-pole axial orthogonal cylindrical magnet - (total stoke is roughly two times the magnet's diameter)

Dimension impact	Gradient field norm		Total relevant stroke		Sensor angle range	
↑ Diameter (D)	••	Increase	•••	Increase	••	Increase
↑ Length (H)	•	Decrease	•	Increase	•	Decrease
↑ Air gap (AG)	•••	Decrease	••	Decrease	•••	Decrease

The air gap is the dominant factor when considering the field norm and angle range. When considering the total stroke, the diameter is dominant. The length is contributing the least. The design for the orthogonal model is more critical than the parallel model as the diameter contributes the most to the volume of the magnet.

Three-pole axial (sinusoidal) parallel cylindrical magnet – (total stroke is ~ magnet's Length/1.5)

Dimension impact	Gradient field norm		Total relevant stroke		Sensor angle range	
↑ Diameter (D)	•	Increase	•	Increase	•	Decrease
↑ Length (H)	••	Decrease	•••••	Increase	•••	Decrease
↑ Air gap (AG)	•••	Decrease	•	Increase	•	Decrease

The airgap (AG) has a dominant impact on the gradient field norm. The Length (H) has a dominant effect on the total stroke length, which is roughly 1.5 times the length of the total stroke. The diameter (D) and airgap (AG) has a minor impact on the stroke length. This same conclusion applies to the sensor's angle range.

Three-pole axial parallel cylindrical magnet – (total stroke is ~ magnet's magnet length)

Dimension impact	Gradient field norm		Total relevant stroke		Sensor angle range	
↑ Diameter (D)	•	Increase	•	Increase	•	Decrease
↑ Length (H)	••	Increase	•••••	Increase	•••	Decrease
↑ Air gap (AG)	•••	Decrease	•	Increase	•	Decrease
↑ Space (S)	••	Decrease		-		-

The trends of the diameter (D) length (H) and airgap (AG) is very similar to the three-pole sinusoidal magnet. Also, the length requirement of the magnet is ~1:1 to the length of the total stroke instead of ~1.5:1 relation for the sinusoidal magnetized magnet. What's more, the space (S) between two magnets has an impact on the Bz-field, gradient-field, and bias error only in the center area of the total stroke. There is no apparent impact on the stroke length and angle range.

12. Disclaimer

IATF 16949 and ISO 14001 Certified