Application note

MLX90423 - Long Stroke Linear Application

Contents

1 Scope

This application note provides a step-by-step guideline to start a long stroke, usually longer than +/- 15mm[1], linear application with stray-field immunity design in combination with main stream Triaxis® sensors MLX90423.

This design of the magnetic angle measurement system is based on the needs of the particular application, such as the available airgap, accuracy requirements, temperature range and properties of the Triaxis® Hall sensor.

A thorough understanding of the Triaxis® Linear Legacy sensing and Linear Stray-field Immune (SFI) sensing[1] is required to continue reading this document.

[1] Check Application Note Dual-disk Stray field Robust Position Sensing

2 Related Melexis Products

MLX90423 Triaxis® Linear Stray-field Immune position sensor featuring Analog/ PWM/ SENT

3 Points of attention

Although stray-field immunity is obtained in the Linear Stray-field Immune sensing mode, with the same magnet design in the linear application, there are two major concerns in the Linear SFI mode compared to Linear Legacy mode:

1. Performance reduction due to less Signal strength[2]
2. ThetaR2P[3] over 360 degrees, period roll-over

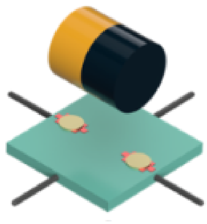

Figure 1 - Linear Stray-field Immune (SFI) mode

The concerns are illustrated below by use one two-pole magnet as Figure 1 shows:

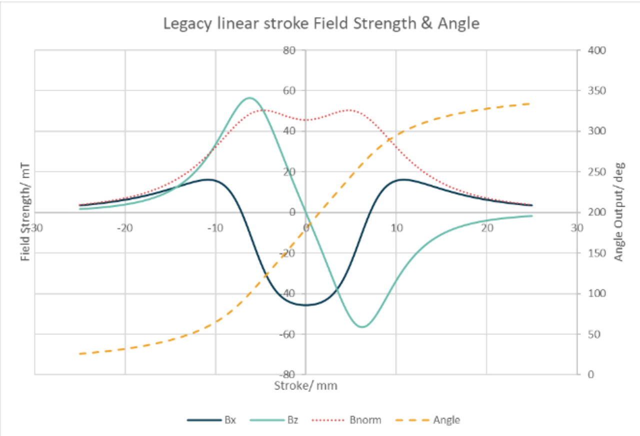

Figure 2 - Linear Legacy mode useful signal & ThetaR2P

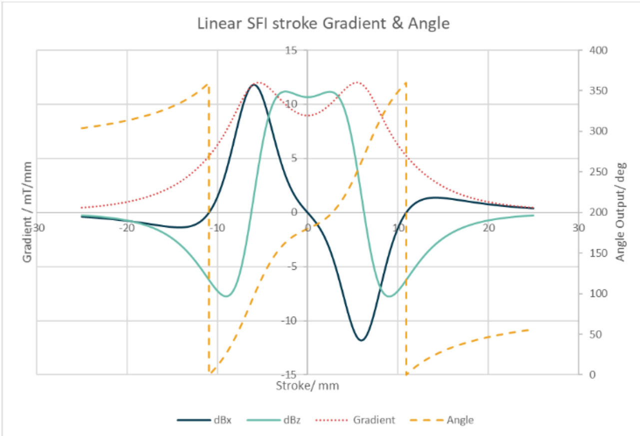

Figure 3 - Linear SFI mode useful signal & ThetaR2P

In Figure 2&Figure 3, the useful signals for both sensing modes are indicated as solid curves as Bx/Bz or dBx/dBz. The signal strength and calculated ThetaR2P are highlighted in dotted curve and dashed curve.

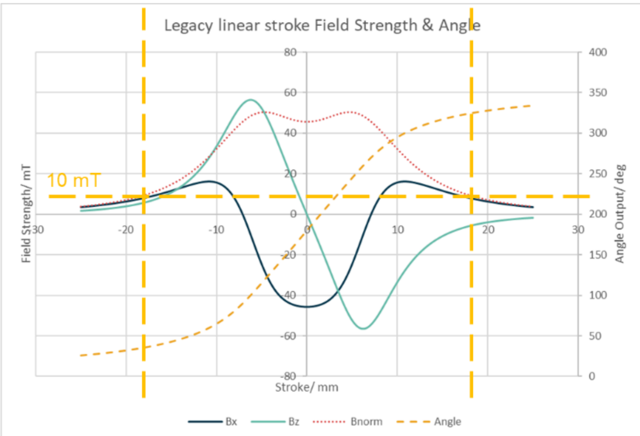

Figure 4 - Linear Legacy mode limitation

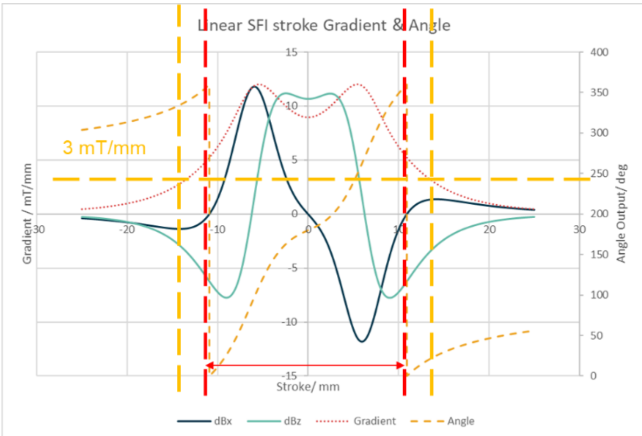

Figure 5 - Linear SFI mode limitation

[2] Legacy mode: Field Strength; Linear SFI mode: Gradient
[3] Legacy mode: atan2(Bz/IMC_gain, Bx); Linear SFI mode: atan2(dBx, dBz/IMC_gain)

The performance limitations from the signal strength are shown in Figure 4&Figure 5 in Dashed Orange curves, as the minimum 10mT field strength requirement for Linear Legacy mode and 3mT/mm gradient for Linear SFI mode, which determines respectively the stroke length not longer than +/- 17mm or +/-14mm.

In spite of the signal strength limitation, the exact useful stroke length for Linear SFI mode is even shorter as in Figure 5 Dashed Red curves show. Theoretically, sensor output angle can't exceed 360 degrees period, otherwise a roll-over in the output occurs. This phenomenon might be more severe than less accuracy due to lack of signal strength.

Consequently, the actual max stroke length for Linear SFI mode is limited to +/-10 mm in this example in Figure 5 and typically +/- 15mm[1] as a concrete performance limitation in all cases by using only one two-pole magnets.

Method	SFI	MAX stroke length	Magnet length	Magnet Complexity	Accuracy
Linear Legacy 2-pole	-	50 mm	30 mm	+	+
Linear SFI	+	30 mm	20 mm	+	+

Table 1 - Summary of existing linear motion solutions

MAX stroke length stated in Table 1 considers both concerns, the performance limitation from signal strength and the period roll-over. In addition, there's no actual limit for Linear Legacy 2-pole, as long as there's sufficient field and no IMC saturation.

Furthermore, compared to the typical Triaxis® Linear Legacy mode used for linear motion where Bx and Bz signal are from one disk, MLX90423 has performance improvement on this mode.

The MLX90423 Linear Legacy mode (with -4xx order code) features in using the sum signal of Bx and Bz from two disks, to achieve a better drift performance under same signal strength.

Method	Symbol	Min.	Typ.	Max.	Unit	Condition	
Linear Legacy 2-pole	$\partial\theta_{TT\_XZ}$	-0.6		0.6	Deg	20mT	160 °C
		-0.8		0.8		10mT	
MLX90423 Linear Legacy		-0.4		0.4		20mT	
		-0.55		0.55		10mT	

Table 2 - Drift performance improvement in MLX90423 Linear Legacy mode

4 Long Stroke Methodology

In order to resolve the mentioned two concerns and to achieve an even longer stroke with stray-field immunity, there are mainly 3 possible approaches:

1. Magnet Threshold Output Clamping[4]
2. Nonius Magnet[5]
3. Long thin magnet[6]

4.1 Magnet Threshold Output Clamping

In some applications, the output is requested as partially linear and partially clamped.

[4] Company proprietary technology
[5] Company proprietary technology and magnets
[6] Company proprietary technology

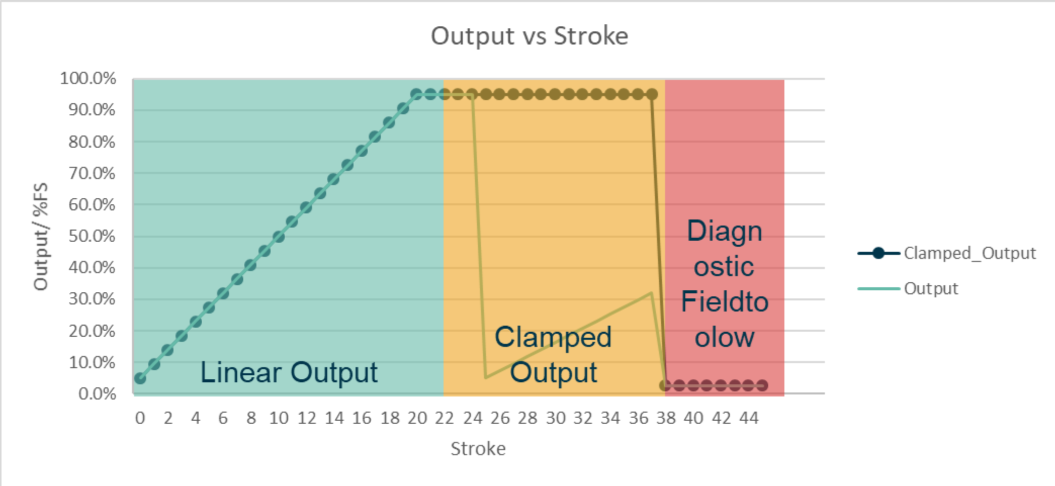

Figure 6 - Long stroke output with clamping range

Figure 6 shows a simulated example of how the output will look like if the Magnet Threshold Output Clamping method is applied or not. The output roll-over from period roll-over is prevented by the clamping, hence the total stroke range can be extended from 24mm to 36mm, until Fieldtoolow diagnostic.

4.1.1 Principle

This method introduces a new parameter ***EXTENDED_RANGE_THRESHOLD***.

Similar to other diagnostic field threshold parameters, such as *DIAG_FIELDTOOLOWTHRES*, this 4-bit parameter ***EXTENDED_RANGE_THRESHOLD*** sets output into CLAMPHIGH[7] level, if the field magnitude is below the threshold. Therefore, the rapid output change from the ThetaR2P period roll-over is avoided.

4.1.2 Implementation

Below is a comparison among different field threshold parameters.

Name	Bit	Range	Resolution
FIELD_STRENGTH	16	[0, 6553.5] mT/mm	0.1 mT/mm
EXTENDED_RANGE_THRESHOLD	**4**	[0, 7.5] mT/mm	0.5 mT/mm
DIAG_FIELDTOOLOWTHRES	**4**	[0, 7.5] mT/mm	0.5 mT/mm

Table 3 - Field threshold parameters

The ***EXTENDED_RANGE_THRESHOLD*** should be selected carefully to guarantee the period roll-over stays in the clamped output range, meanwhile the value is above the *DIAG_FIELDTOOLOWTHRES* to ensure the functionality of field too low reporting.

Here are two examples from a typical 2-pole magnet measurements, with either Analog/PWM or SENT output protocol. In both examples, the output clamping method are applied, where ***EXTENDED_RANGE_THRESHOLD*** = 5mT/mm and *DIAG_FIELDTOOLOWTHRES* = 1.5mT/mm. Besides, the default sensor configuration includes DP = 0 and without output linearization calibration, which means output will be proportional to the ThetaR2P value.

[7] ACA version

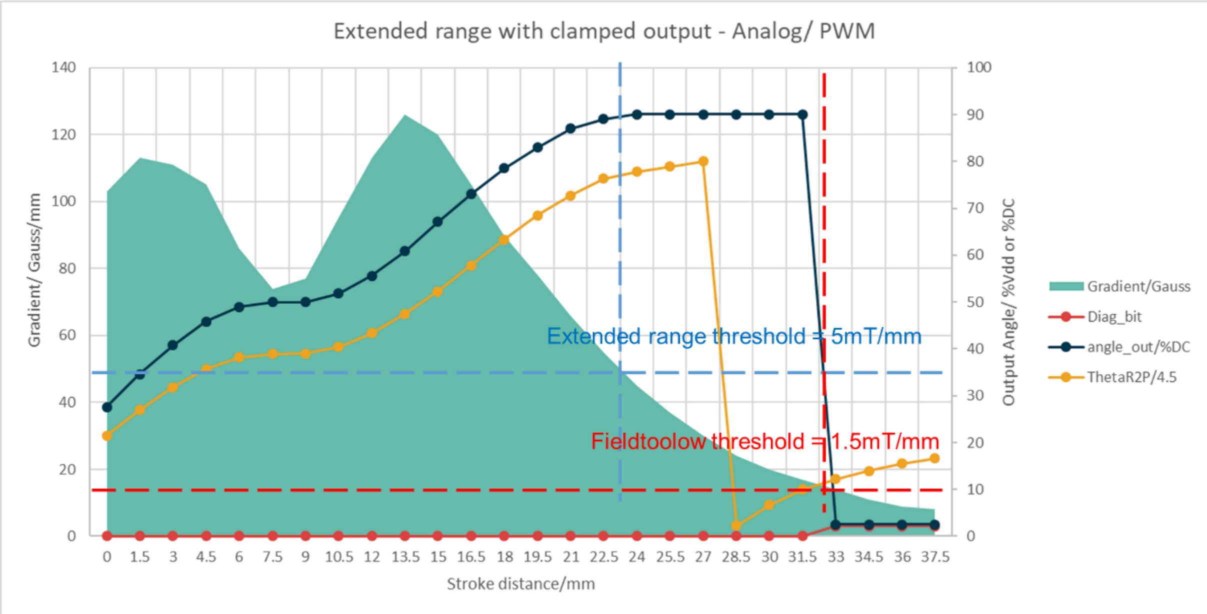

Figure 7 - Output clamping method example in Analog/PWM output protocol[8]

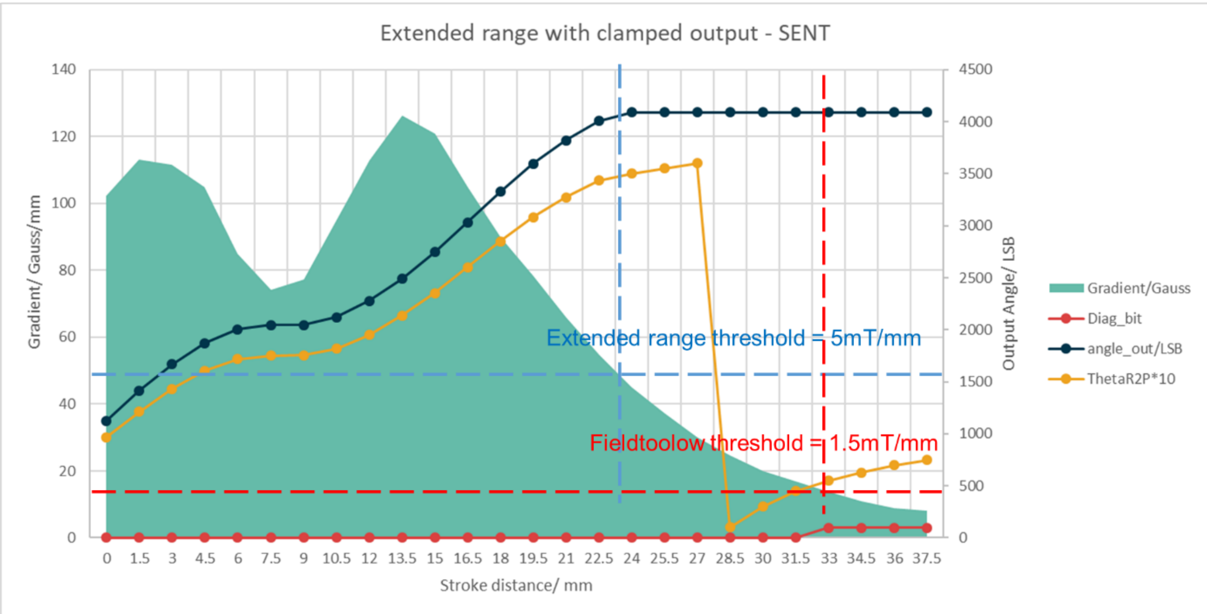

Figure 8 - Output clamping method examples in SENT output protocol[8]

As shown Figure 7&Figure 8, though a period roll-over occurs between stroke range [27, 28.5] mm, output remains CLAMPHIGH. Moreover, if the magnet moves to stroke position larger than 33mm, FIELDTOOLOW diagnostic in the output or the diagnostic bit in the slow channel is successfully set.

In this case, the stroke length is “extended” from originally 24mm to 33mm, consisting of 24mm linear output and 9mm clamping output.

Additionally, there’s an added feature only in SENT output protocol, where fast channel 1 remains at CLAMPHIGH if FIELDTOOLOW diagnostic is reported, as shown in Figure 8.

[8] ThetaR2P values are scaled to match the plot

4.2 Nonius Magnet

In addition to clamp the period roll-over output with field threshold, MLX90423 also develops a brand-new technique in generating a linear output by crossing up to 3 period roll-overs, or 4 periods as up to 1440 degrees, with Melexis proprietary multipole Magnet[9].

The benefit of using this technique and the magnet is not only to reach a longer stroke (feasible max length around **50mm**), but also to optimize the accuracy of the full stroke.

4.2.1 Nonius concept

Nonius concept is used to determine a unique accurate absolute position by means of two periodic signals, master signal and Nonius signal, with different period length. The master signal is used to provide the accurate position and the Nonius signal to provide the absolute position.

4.2.2 Reference Magnet

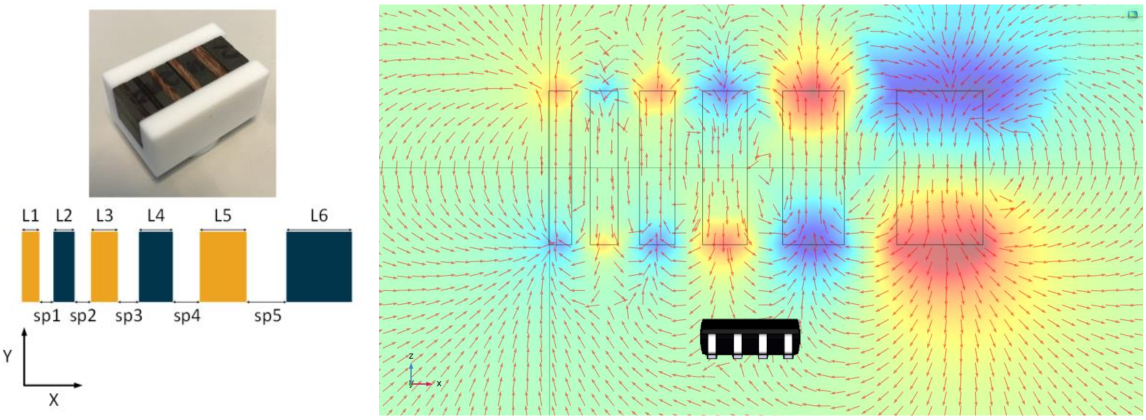

Figure 9 - Reference Magnet from Melexis and its polarity on XY plane (left) and XZ plane (right)

This reference magnet has a length of 28mm (starts from X axis 0mm) and consists of 6 magnets in total, with different length Lx and varying gaps spx and toggling magnetization magnetized from Z direction. MLX90423 is placed underneath the magnet in the centre position on Y axis with a certain airgap on Z axis, and magnet or sensor moves along the X axis.

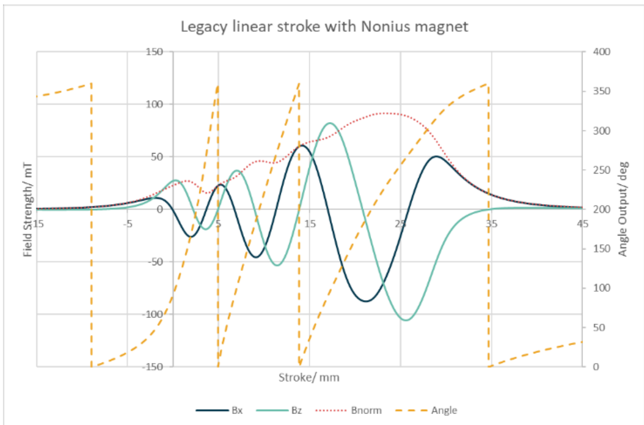

Figure 10 - Linear Legacy mode useful signal & ThetaR2P

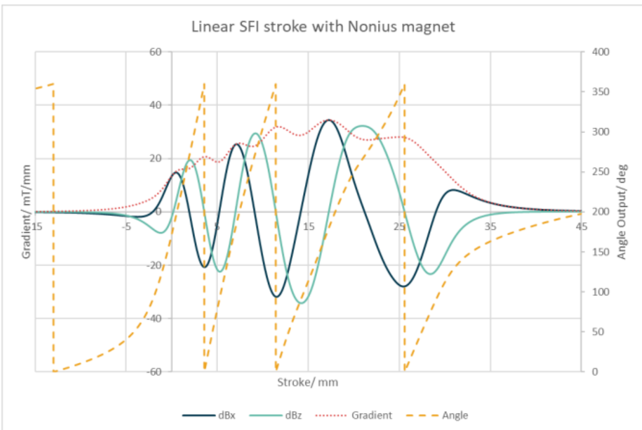

Figure 11 – Linear SFI mode useful signal & ThetaR2P

[9] Reference Melexis proprietary magnet can be provided on request.

4.2.3 MLX90423 Nonius sensing Principle

In MLX90423, one periodic signal is the ThetaR2P over the stroke, measured by the Linear SFI sensing technique, used as master signal.
The plot below shows the ThetaR2P over stroke with the reference magnet at the airgap of 2.4mm.

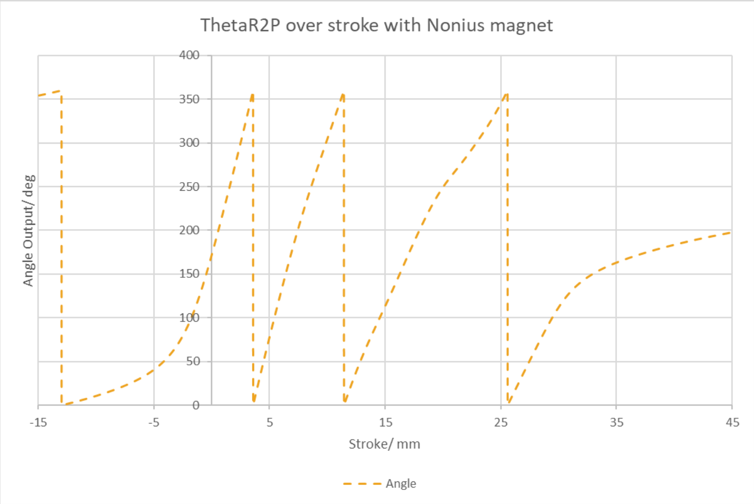

Figure 12 - ThetaR2P over stroke with the reference magnet at airgap 2.4mm

Without Nonius technique, the 3 period roll-overs in measurement will result in 3 rapid changes in the output. Due to the new feature of toggling sensing mode between Linear Legacy and Linear SFI, MLX90423 is capable of measuring both Field Strength $|B|$ and Gradient $|\Delta B|$, at the same position in two measuring slots. Hence the Ratio of the Field Strength and Gradient, $|B|/|\Delta B|$ can be calculated.

This $|B|/|\Delta B|$ Ratio plays the role of the Nonius signal.

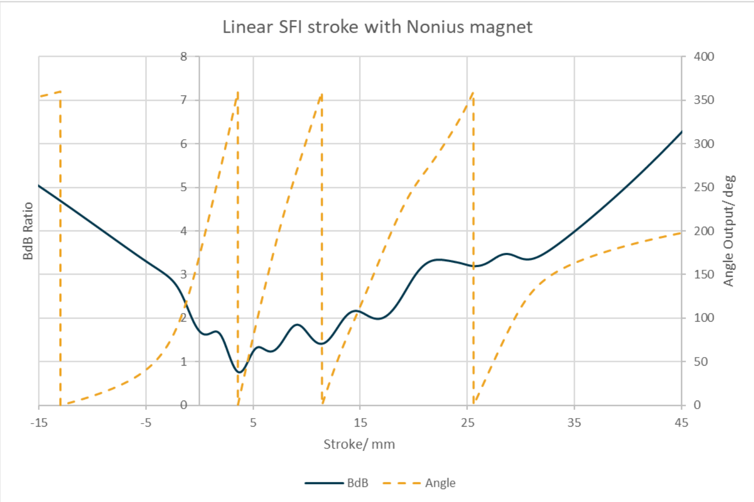

Figure 13 – ThetaR2P and BDB ratio over stroke with the reference magnet at airgap 2.4mm

In combination of the two signals, an accurate absolute position can be calculated.

4.2.4 Output accuracy benefit from Nonius principle

The Triaxis® accuracy specification is always defined by Error in degrees per angular period or 360 degrees.

Due to the new feature of crossing multiple period (360 degrees) roll-over, there's an additional benefit to implement the Nonius principle in the design to optimize the accuracy performance.

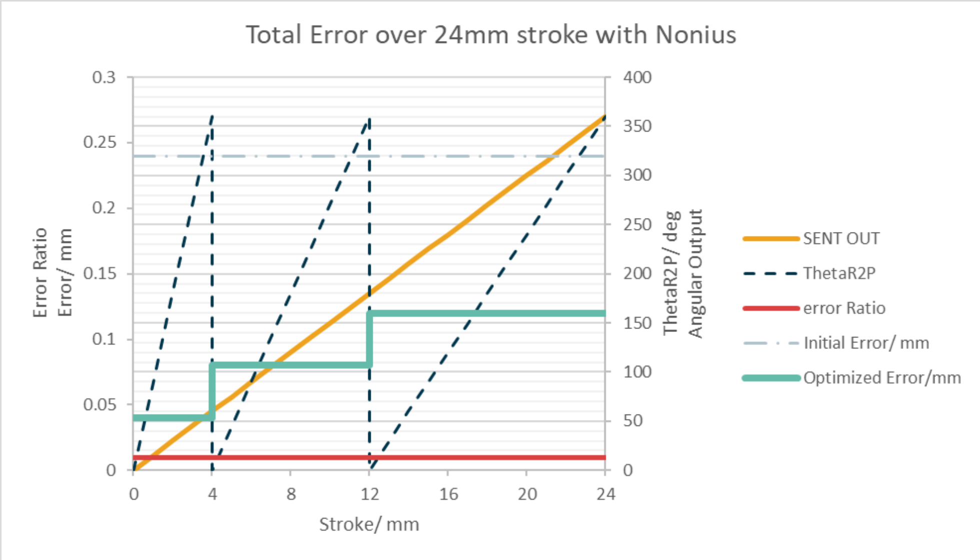

Figure 14 – Output Accuracy benefit illustration with Nonius principle

This example is based on an extreme error condition in a 24mm linear stroke application, where the total error has a ratio of 1% of full span of 360 degrees period. With the original Linear SFI sensing principle, the total error is 0.24mm in 24mm as the grey dash-dotted line indicates.

By implementing the Nonius Magnet and sensing principle, with crossing 3 angular periods among 4, 8 and 12mm, the total error per period will be reduced to 0.04mm, 0.08mm and 0.12mm as the green line indicates – maximum reduced to 50% of original one. Meanwhile a higher accuracy in the beginning of stroke (0.17% in the first 4mm stroke and 0.33% in the 8mm stroke) can be achieved.

4.2.5 Implementation[10]

There are 8 parameters in total to configure this new feature.

Parameter	R/W	Description	Bits
CodeSENSING_MODE_EXTENDED_RANGE_EN	R/W	Enables extended range for linear stray field immune sensing mode	1
CodeEXTENDED_THETA_MIN	R/W	Threshold ThetaR2P value where the extended range starts, range between [0, 1440] degrees	12
CodeEXTENDED_THETA_MAX	R/W	Threshold ThetaR2P value where the extended range ends, range between [0, 1440] degrees	12
CodeEXTENDED_C0	R/W	Configuration parameter for angle calculation in Extended Range sensing mode, C0, range between [-8, 8]	16
CodeEXTENDED_C1	R/W	C1, range between [-3.13e-2, 3.13e-2]	16
CodeEXTENDED_C2	R/W	C2, range between [-2.44e-4, 2.44e-4]	16
CodeEXTENDED_C3	R/W	C3, range between [-9.54e-7, 9.57e-7]	16
CodeEXTENDED_C4	R/W	C4, range between [-9.31e-10, 9.31e-10]	16

Table 4 - Nonius sensing parameter list

[10] Contact Melexis for technical support. If the implementation is faulty or incompatible, a large error may occur. The design should always be tested and verified during the design validation and the user assumes full responsibility for any consequences of their design choices.

Below shows how to implement the parameters in the Nonius sensing algorithm step by step.

1. The correlation between the BDB and ThetaR2P to determine the correct extended angle range is:

$$BDB = C_0 + C_1\theta_{extended} + C_2\theta_{extended}{}^2 + C_3\theta_{extended}{}^3 + C_4\theta_{extended}{}^4$$

Equation 1 - Extended angle (θextended) calculation formula

Where

$$\theta extended_i = ThetaR2P + i * 360 \ (i = \{0, 1, 2, 3\})$$

Equation 2 - All possible ϑextended

2. Define the range of $\theta_{extended}$

$$\theta_{extended\_MIN} < \theta_{extended} < \theta_{extended\_MAX}$$

Equation 3 - θextended range definition

3. Compute $BDB[\theta extended_i]$ for each possible $\theta extended_i$ from Equation 1

4. Search for the minimum deviation between the measured $|B|/|\Delta B|$ and calculated BDB:

$$\min(abs(\frac{|B|}{|\Delta B|} - BDB[\theta extended_i]\,))$$

Equation 4 - Searching minimum deviation

5. Define output angle as the $\theta extended_i$ with the smallest error

An example of how to calculate the parameter is explained in the following sections.

4.2.5.1 Define the ϑextended range

After enabling the Nonius sensing mode by setting ***SENSING_MODE_EXTENDED_RANGE_EN*** = 1, the next step is to define the θextended range of the long stroke.

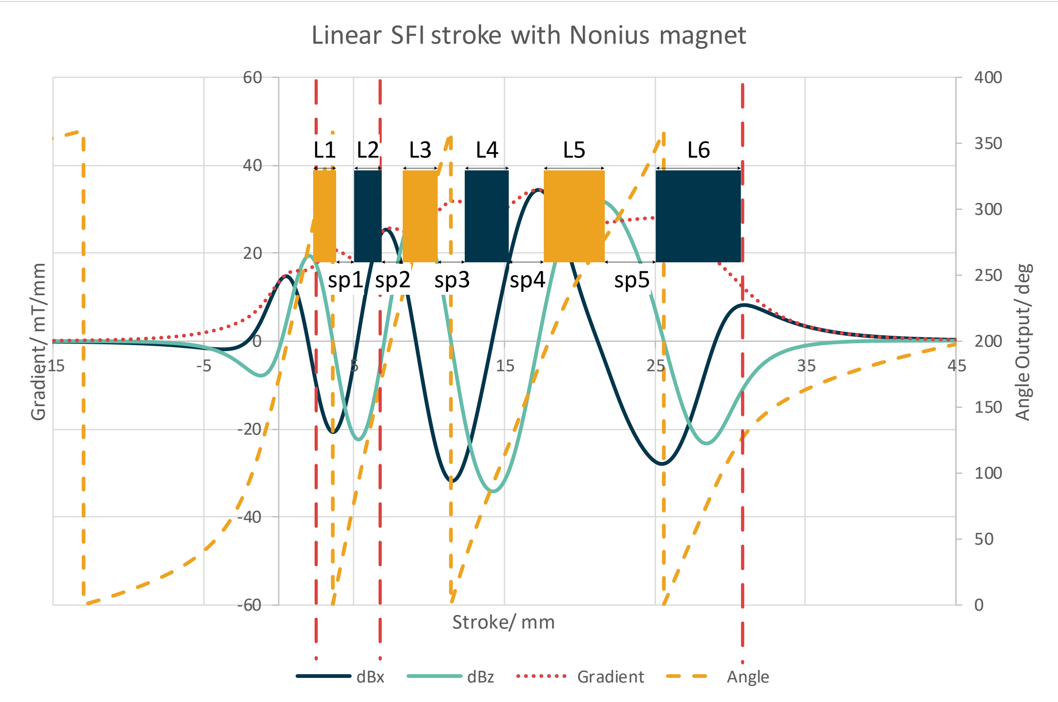

Figure 15 - BDB and ThetaR2P along the stroke in different magnetic angle period

Figure 15 shows the illustration of Nonius magnet BDB and ThetaR2P over the stroke, in combination with the magnet size, whose first magnet starts from X axis 0 mm.

To make it more intuitive, the ThetaR2P over stroke can be separated into multiple magnetic angle periods and different period highlighted in different colours, with alignment to the reference magnet.

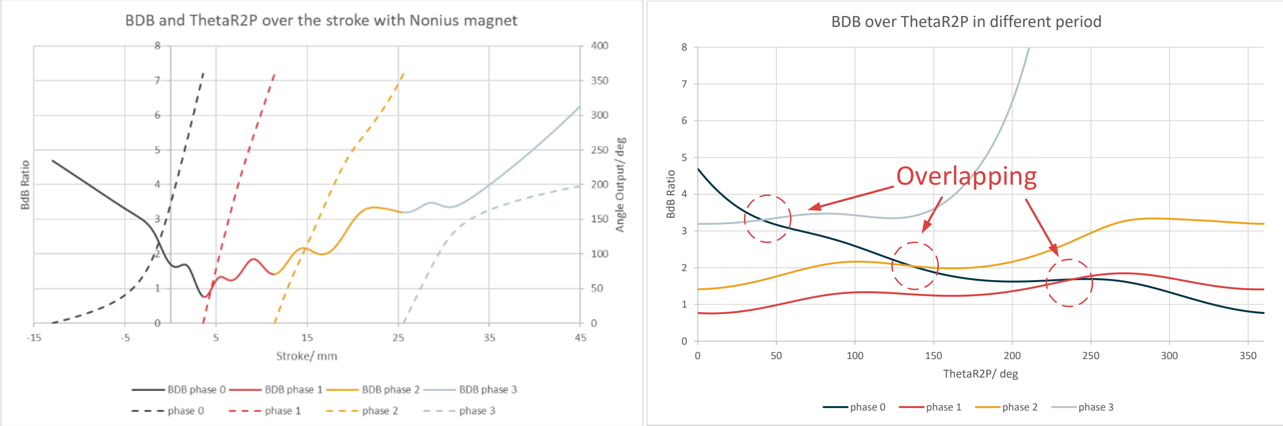

Figure 16 - BDB over ThetaR2P along the stroke in different period

The BDB over ThetaR2P is derived from Figure 15, with also different colours respectively as shown in the left plot of Figure 16.

As indicated in the right plot Figure 16, phase 0 has overlaps with other phases. Considering Equation 4, to ensure the unique minimum deviation in the entire stroke, overlapping in the BDB over ThetaR2P correlation should be avoided.

There are mainly two ways to escape from overlaps, and the first one is to locate the last overlapping point from [0, 360] degrees. In consequence, ***EXTENDED_THETA_MIN*** should be bigger than the largest overlapped ThetaR2P value, for example 250 degrees. Similar to this, the ***EXTENDED_THETA_MAX*** can be defined as 1200 degrees.

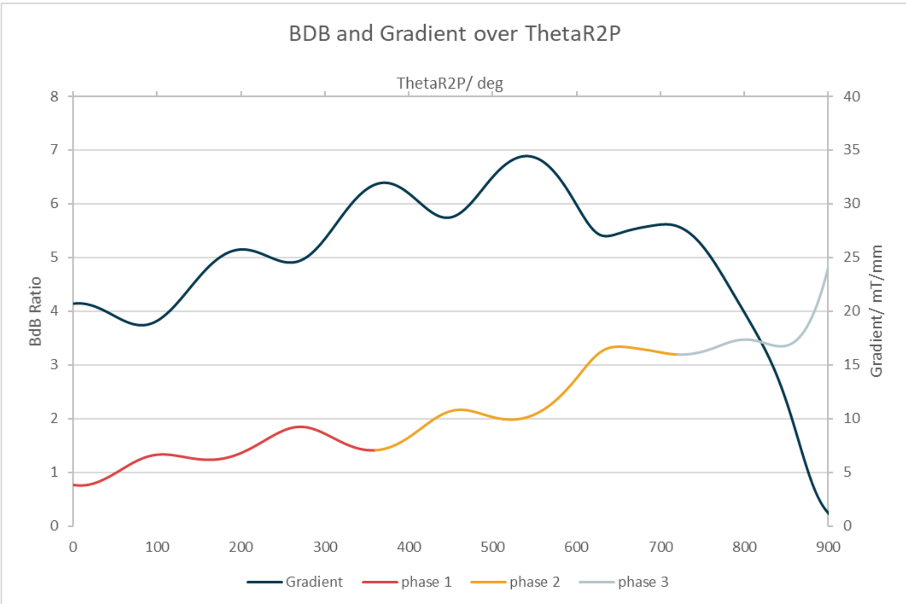

Figure 17 - BDB over ThetaR2P excluding phase 0

The other way is to completely discard the phase 0 and start the long stroke with phase 1, as shown in Figure 17. In this case the ***EXTENDED_THETA_MIN*** value can be simply defined to 0 with also sufficient margin to the overlapping and the stroke starting point is the edge of the second magnet. Though the first two magnets are neglected, or around 3mm on the X axis, more stability and less design complexity is reached. The

EXTENDED_THETA_MAX will be defined by the gradient strength >6mT/mm (or 3mT/mm for limited performance) as the end point of the stroke with some margin, at 900 degrees or 33mm on the X axis.

4.2.5.2 Calculate the Cx

The build-in 5 Cx coefficients can be used to form the line estimation formula up to 4th order polynomial of the BDB over ThetaR2P curve in Figure 17.

Below show two examples, a monotonic linear curve and a 4th order polynomial.

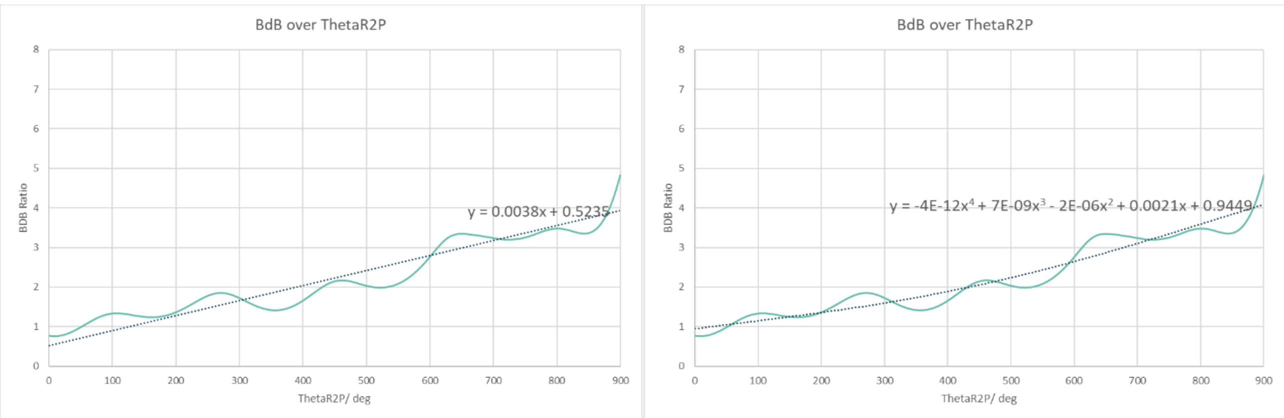

Figure 18 - BDB over ThetaR2P with linear or 4th order trend line

By programming the Cx parameters accordingly, deviation with different i values is calculated with Equation 4 as below, example shows only the linear trend line:

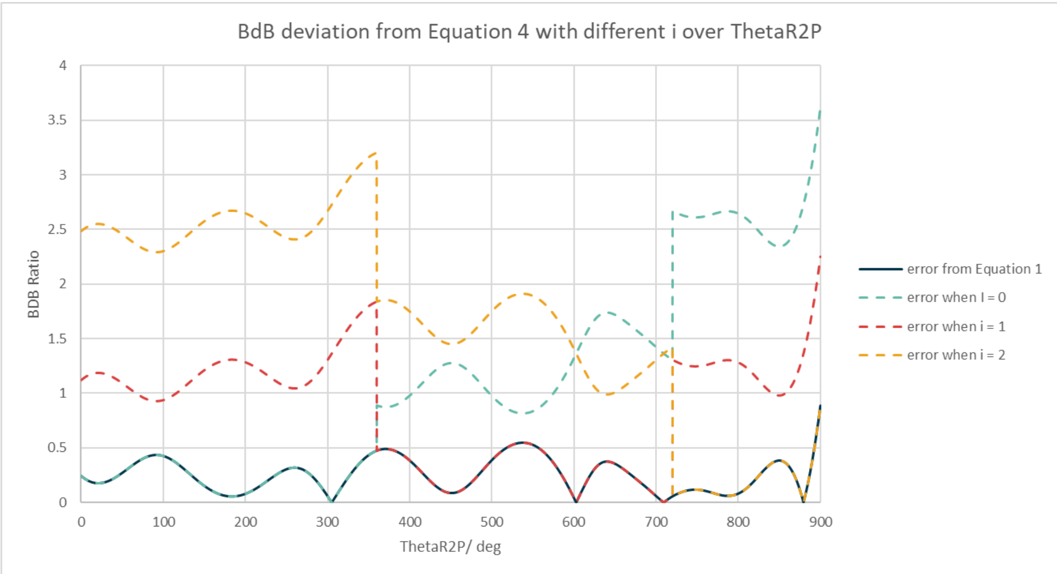

Figure 19 - BDB deviation from Equation 4 with different i value

The calculated deviation from Equation 1 remains the minimum over different i values, which guarantees there will be no sudden jump in the output can occur in the working stroke range.

4.2.6 50mm stroke feasibility

The previous example shows the feasibility of using a 28mm Nonius magnet to reach 30mm stroke, with only 2 period roll-overs used and maximum BDB < 5. By extending the Nonius magnets from 6 to 8 (with each magnet length increasing accordingly), a stroke up to 50 mm can be achieved.

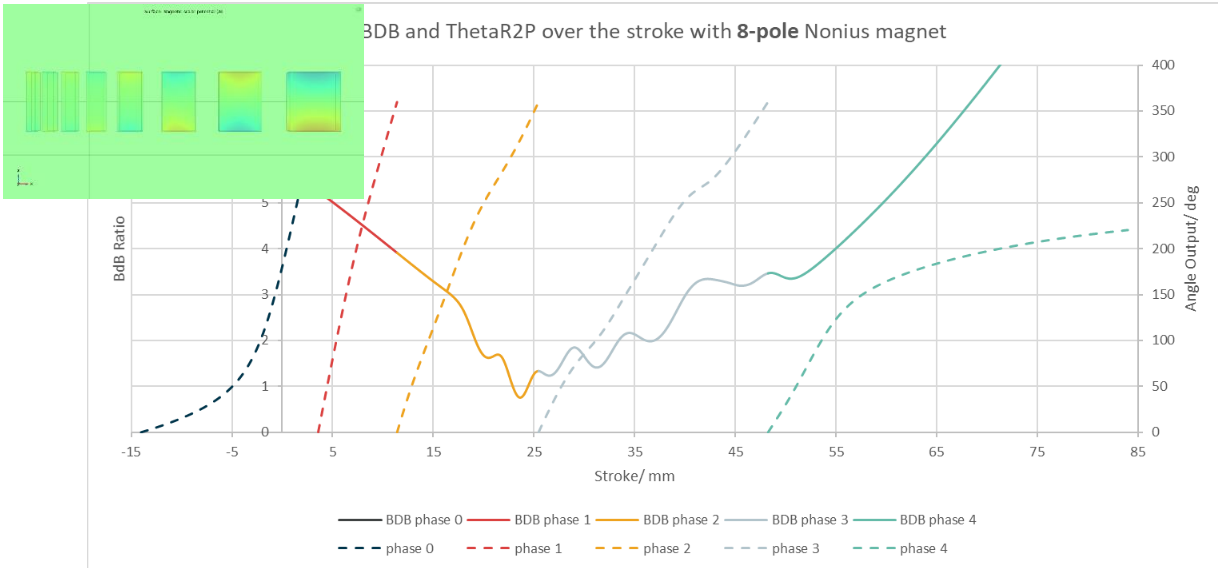

Figure 20 - BDB and ThetaR2P along the stroke in different period, with 8-pole Nonius magnet illustration

4.3 Long Thin Magnet

Another way to achieve long stroke is to use a Melexis proprietary application, with a long but thin magnet, whose magnetization direction is along the thinnest edge, and slightly rotated away from the moving axis.

This cost-efficient method suits the design targeting simple long stroke application with less magnet material, as well as less full stroke accuracy is acceptable.

4.3.1 Principle

The typical linear stroke application with a single two-pole magnet looks like below:

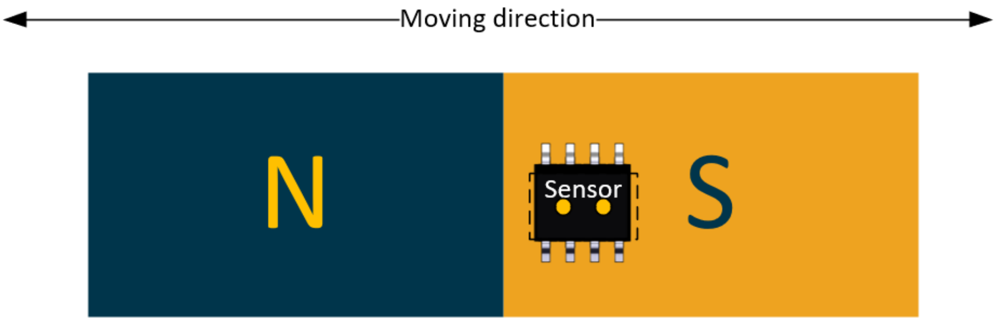

Figure 21 - Typical linear stroke application, top view

The sensor is usually placed underneath the magnet, whose movement is aligned with the requested stroke. The two dots indicate the two hall plates in the Linear SFI.

As mentioned in Chapter 3, the two concerns limit the maximum stroke length to a typical length of +/- 15mm. Instead of only extending the magnet length along the stroke moving direction, the new approach is to convert the long stroke into an equivalent shorter stroke, which is perpendicular to the original moving direction (EP_S).

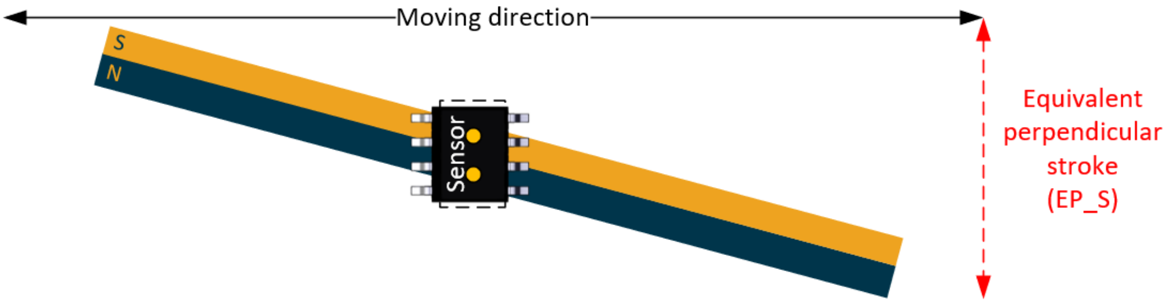

Figure 22 - Equivalent perpendicular moving stroke, top view

With the help of EP_S, the complex long stroke situation is brought back to the familiar typical length where the satisfactory stray-field immunity and performance of the Linear SFI mode is empirically known.

This principle can also be applied in Linear Legacy Sensing mode or combining stray-field immune mode with the Nonius Magnet principle as well, in order to achieve a longer stroke with relatively less material.

4.3.2 Implementation

As Figure 22, the top view shows, the magnet design is very straight forward and easy to implement. Compared to the typical single two-pole magnet design, the only two changes are the magnetization direction and a slight rotation.

A recommendation for the length of EP_S and magnet dimension are as follows:

Dimension	Recommended length/ mm
EP_S	[6, 12]
Magnet Width	[1, 6]
Magnet Height	[5, 10]
Stroke Length	[30, 60]
Magnet Length	$\sqrt{EP\_S^2 + Stroke\_length^2}$

Table 5 - Recommended dimension of long thin magnet design

A rotation of the magnet to the stroke moving direction is required. The rotation angle is calculated with the ATAN2 formula:

$$Rotation\ Angle = \mathrm{ATAN2}(EP\_S, Stroke\_length)$$

Equation 5 - Magnet rotation angle calculation

With this magnet dimension, the useful angle range of the Linear SFI sensing mode can go up to 200 degrees, meaning the resolution of this application is [0.15, 0.3] deg/mm.

Last but not least, the study and measurement are done with Neodymium magnet. The other magnet material can also be selected but airgap is required to be adjusted accordingly.

4.3.3 Eccentricity performance

In general, the eccentricity on the XY plane is equivalent to the stroke movement along the original stroke or the EP_S. The study of eccentricity in this Application Note is only focusing on the Z axis, or in other words, dynamic airgap.

The reference magnet used for this study is a Neodymium magnet with magnet length of 50mm, 5mm in height and 2mm width. It's magnetized in width direction. The dynamic airgap is between [-0.5, 0.5] mm and the different airgaps are studied within {3, 3.5, 4, 4.5, 5} mm.

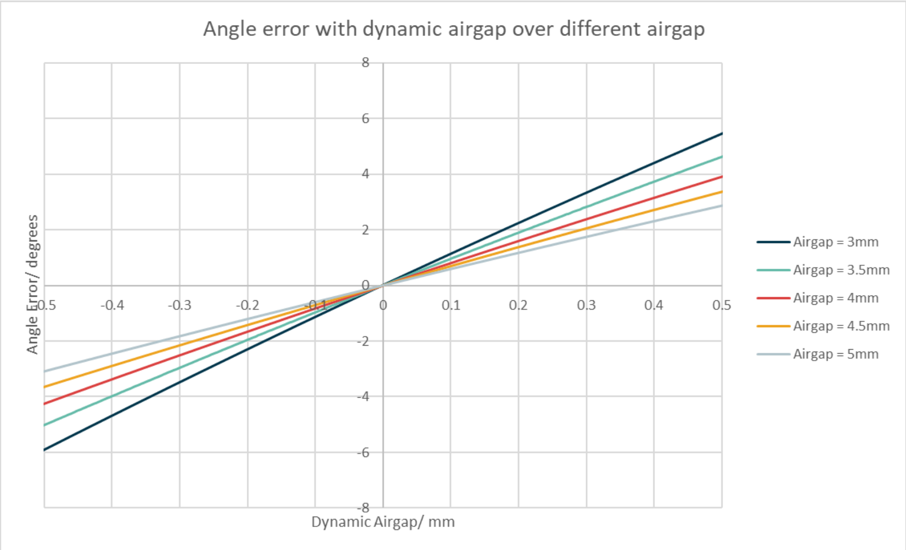

Figure 23 - Angular error from dynamic airgap in different airgaps

The smaller the airgap, or the closer the dynamic eccentricity to the magnet, the bigger the angular error is. The worst case, when there's 3mm airgap, the maximum dynamic airgap impact can be 1.2 degrees per 0.1mm dynamic airgap, which is 0.6% of the full span.

5 Conclusion

The 3 methodologies mentioned above provide a starting point of stray-field immune long stroke design. Below we list again the typical magnet length vs stroke length and essential characteristics per design, compared to the reference Linear Legacy 2-pole and Linear SFI design.

Method	SFI	MAX stroke length	Magnet length	Magnet Complexity	Accuracy
Linear Legacy 2-pole	-	50 mm	30 mm	+	+
MLX90423 Linear Legacy	-	50 mm	30 mm	+	++
Linear SFI	+	30 mm	20 mm	+	+
Output Clamping	+	40 mm[11]	30 mm	-[12]	+[13]
Nonius Magnet	+	50 mm	50 mm	- - -	+++
Long thin magnet	+	50 mm	50 mm[14]	+	+

Table 6 - Long stroke methodology summary

[11] Including clamping output range
[12] Usually two magnets
[13] Excluding clamping output range
[14] Magnet length in moving direction

6 Revision history

Revision	Date	Change history
001	18-Jan-24	Document creation

Table 7 - Revision history

7 Disclaimer

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