Application note

Sensors For Motor Control Feedback Loops

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1. Scope

This document gives an overview of Melexis position sensors for electrical motors. The intent is twofold. First, the document gives selection guidelines between the three different types of magnetic position sensor IC: latch/switch, linear or resolver. The secondary purpose is to explain general concepts for each magnetic position sensor type. For completeness, this document also refers to Melexis actuator products for electrical motors. The primary audience is electrical and mechanical engineers in motor design looking for ways to use Melexis Magnetic Sensors and Actuators.

2. Contents

3. Introduction

Motor Position Sensors are an important building block for electrical motors. There are two use cases. Firstly, position sensors are for accurate **positioning**. Take for example a valve. The position sensor ensures a correct valve position. Another example is a robot arm where the servo motor accurately positions a joint.

Secondly, position sensors are an integral part of the motor **commutation** control loops for several types of electrical motors. Think of *brushless motors*. The distinction between positioning and commutation is important as some motors have multiple control loops: one control loop for commutation and one control loop for positioning. These control loops do not necessarily use the same sensor.

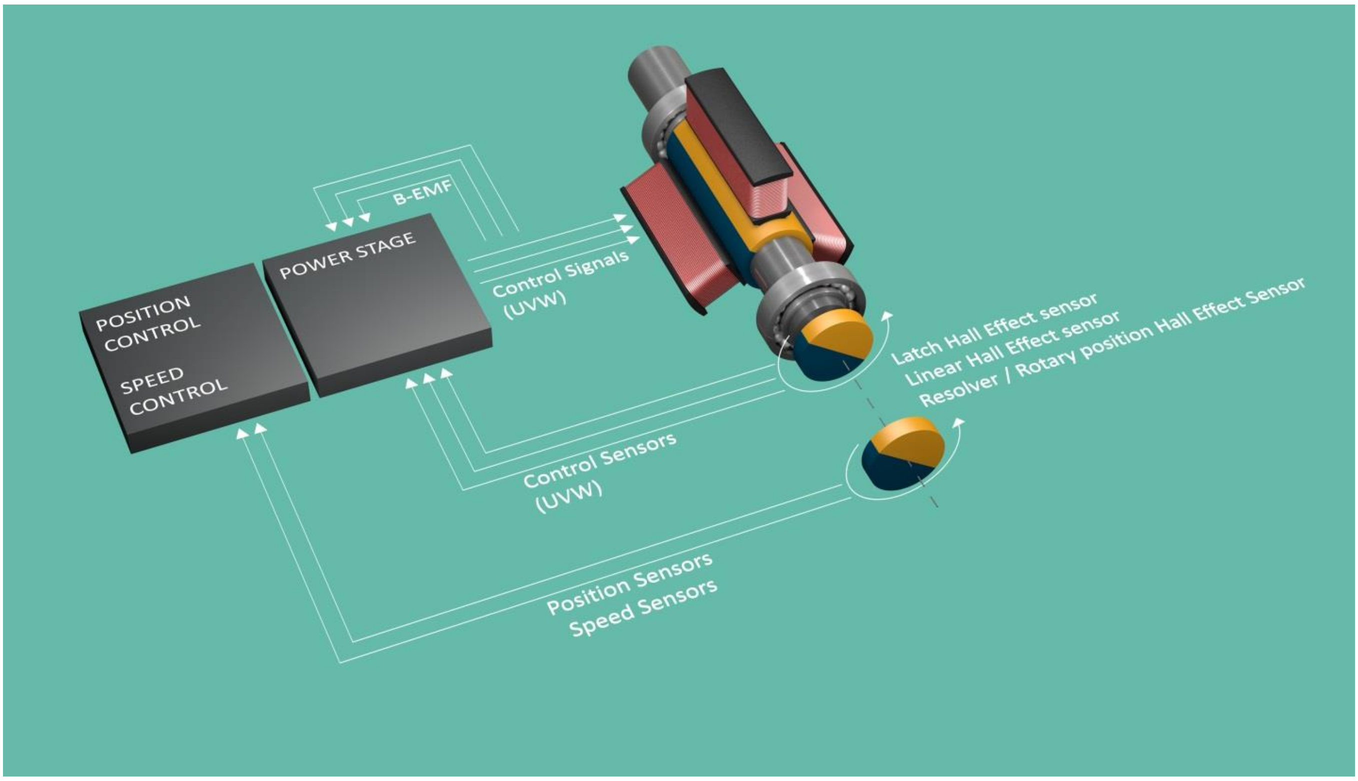

Figure 1: General Building Blocks and communication paths to enable motor commutation and positioning

Let us start with motor commutation. Figure 1 gives the building blocks and position information flow for a brushless motor. The motor control algorithm determines the currents through the coils and the timing of those currents. The angle of applied field has to be in quadrature to the rotor's field direction for maximum efficiency.

The type of motor control algorithm is linked with the motor design and the sensor type. For example, brushless motors can work with trapezoid control, sinusoidal control and field oriented control. Trapezoid control using latch/switch readout of the position typically is sufficient for a Brushless DC motor (BLDC). This concept supports high speed. But, torque ripple might be present and unwanted. Imagine an accelerating electrical car where the acceleration is not smooth. Sinusoidal control or Field Oriented Control oriented control requires an angle with much higher resolution. These control algorithms can also be used for a Permanent Magnet Synchronous Motor (PMSM). These two last algorithms require an accurate angle position of the rotor. The more accurate, the higher the efficiency will be and in some cases even better safety.

Figure 2 and Figure 3 give position readout architectures with magnetic sensors. Figure 2 is a multi-chip configuration. Here, 3 magnetic sensor ICs are positioned next to the shaft. This configuration can be with latch/switch or with linear Hall. If you use latch/switch, you will get a low resolution rotor position of +/-30°. If you use 3 linear halls, the angle can be calculated with high resolution. Figure 3 is another approach with the single chip magnetic resolver. Here, the IC measures two field components which give accurate absolute angle position with high resolution. Multiple resolvers can be used to cross check the signal to improve safety.

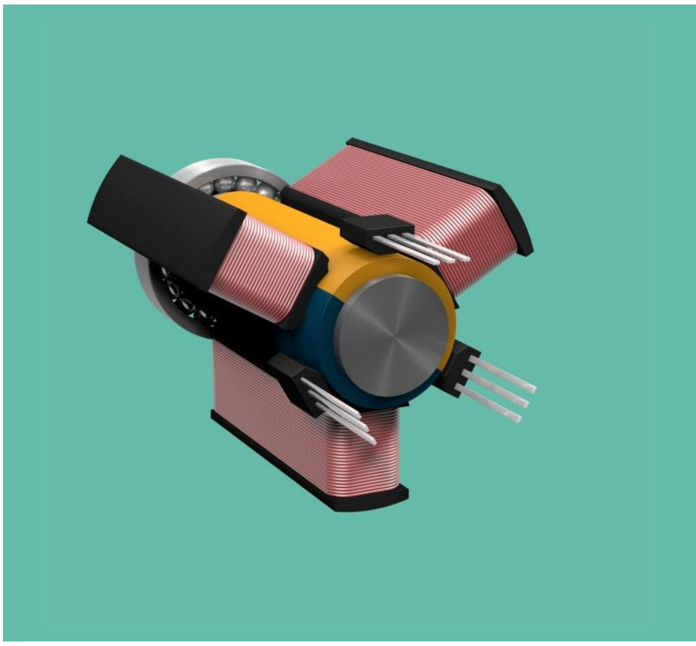

Figure 2: latch and linear principle

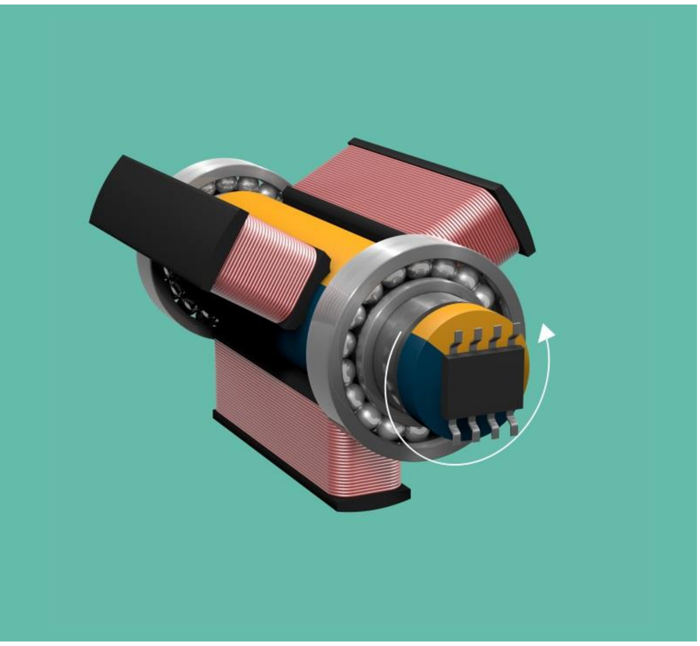

Figure 3: resolver principle

The text above focusses on motor position sensor for **motor commutation**. That being said, some applications such as smart valves also need to position a component. Here, the sensors needed for motor positioning might be the ones used for motor commutation. This is especially true if the rotor shaft's position and the motor's output shaft are 100% correlated. This is not always the case. In some cases, an internal gear box converts a high speed/low torque rotor to a lower speed/higher torque output shaft. It then might be necessary to put an additional –lower speed- sensor on the output sensor.

4. Melexis Products

This chapter gives a high level overview of 3 different hall based product categories for motor commutation & positioning: latch/switch, linear hall and resolver. This section also directs to interesting Melexis products. The subsequent chapters then give more insights in each of these product types.

Motor Sensor Solutions	**Low resolution**	**High Resolution**
Multiple IC solution	Latch/switch	Linear Hall
Single IC Solution **(Multiple ICs possible for redundancy/cross check)**		Resolver

For completeness, the two last sections of this chapter refer Melexis Triaxis 'lower speed' position sensors and Melexis actuators. Triaxis position sensors can complement the sensors to enable accurate positioning. Think of situations with a lower speed application or when the output shaft is decoupled from the rotor shaft by a gearbox. Latch/Switch for positioning is interesting when for example the start/end position is the most important parameter.

4.1. Latch/Switch

Latch/Switch products are placed in the stator in a multi-IC configuration. Think of trapezoid control of a BLDC motor.

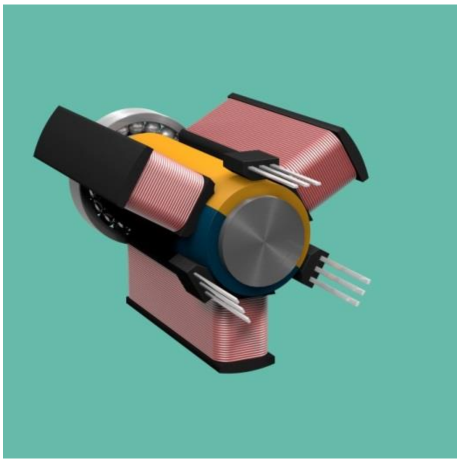

Figure 4

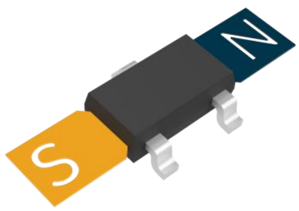

Figure 5: lateral / X-axis

Figure 6: Perpendicular / Z-axis

Melexis provides a whole range of Hall Effect latches with fixed, pre-programmed and programmable parameters. Next to the traditional sensors which are sensitive to the magnetic flux density that is applied perpendicular to the die surface.

The new generation latch can also sense a lateral applied magnetic flux density. This new feature brings a large flexibility in the positioning of the sensor versus the magnet (rotor or sensing magnet). The sensors are available in a single die TSOT-3L or TO92-3L. Melexis also offer the first ASIL-B capable latch/switch on the market.

MLX92211	Hall Latch - New Generation - Pre-programmed thresholds
MLX92212	Low voltage Hall Latch
MLX92221	2 wire Hall Latch - 2nd Generation
MLX92232	End Of Line Programmable 3-wire Hall Latch / Switch
MLX92242	End Of Line Programmable 2-wire Hall Latch / Switch
MLX92292	End Of Line Programmable 3-wire Hall Latch / Switch, ASIL-B
MLX92251	Dual Hall Effect Latch with Speed & Direction - Medium Sensitivity

4.2. Linear Hall

The Melexis high speed pre-programmed second generation linear Hall-effect sensor designed in mixed signal CMOS technology is an analog sensor with an output voltage proportional to the applied magnetic field and to the chip supply voltage (ratiometric). The Output Offset Level (Quiescent Level) at zero magnetic field is equal to 50% of the chip supply voltage.

A linear Hall Effect sensor can be used to replace the hall Latch sensors. Using multiple sensors in quadrature gives the absolute angle of the rotor with high angle resolution. Their analog output makes it possible to calculate, with a dedicated algorithm, a much more accurate rotor position. This makes them not only suitable for detecting the motor commutation point but also for an accurate position control.

Two linear hall sensors placed at a 90° magnetic phase shift can also be used as a sine cosine angle sensor. The angle α is calculated from the arctangent of SIN over COS.

The characteristics of this multi linear Hall Effect sensor configuration are the same as for the resolver sensors which are described in the sections below. As the linear Hall Effect sensors are used a multi-sensor configuration the positioning of the individual sensors is more crucial than on a single resolver sensor configuration.

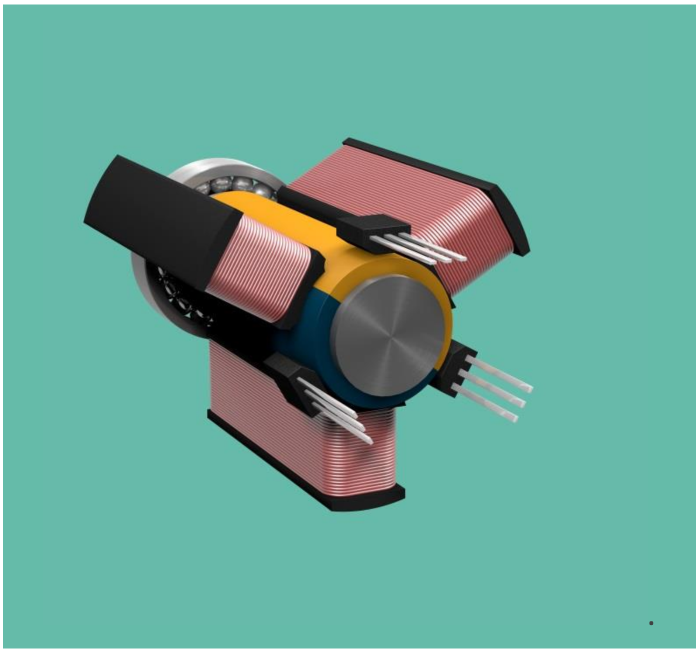
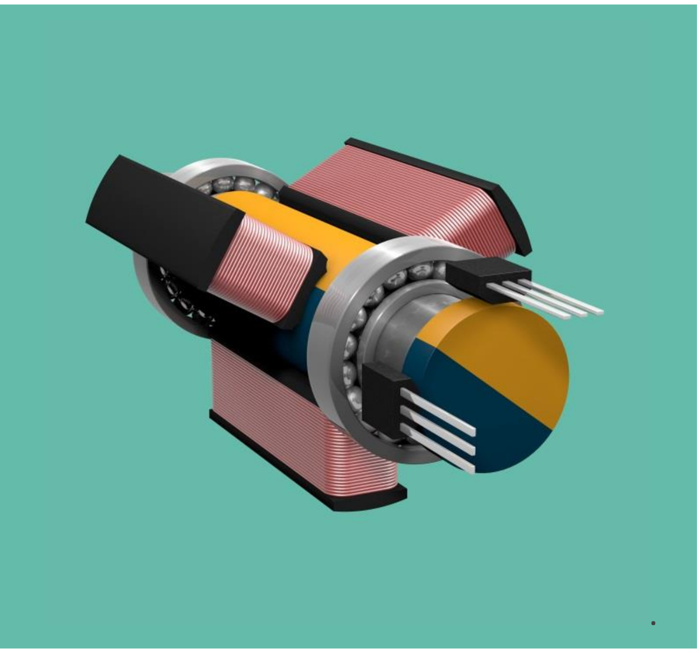

Figure 7: setup with 3 sensors

Figure 8: setup with 2 sensors

MLX90290 High Speed Pre-Programmed Linear Hall IC, analog ratiometric output.

4.3. Resolver

Magnetic Resolvers are single IC solutions which give the sine-cosine of the magnetic signal by two ratiometric outputs. The latest generation can be placed either end of axis or off-axis.

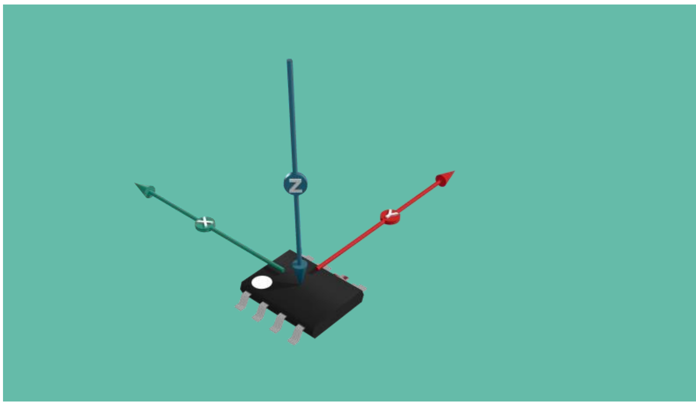
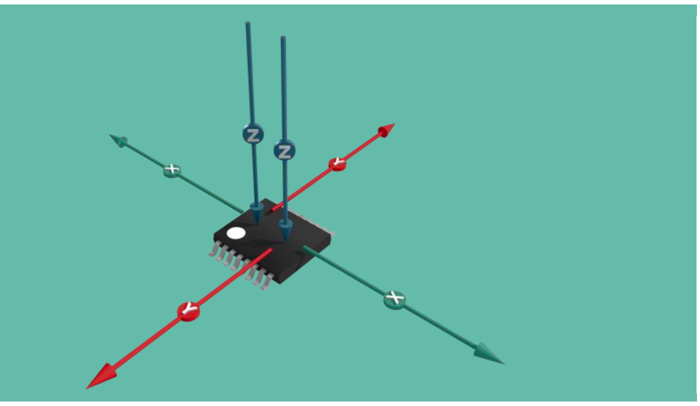

Figure 9: SOIC8

Figure 10: TSSOP16

The Triaxis® Resolver of the new generation has an X-Y-Z magnetic axis configuration to select the sensing plane of the sensor.

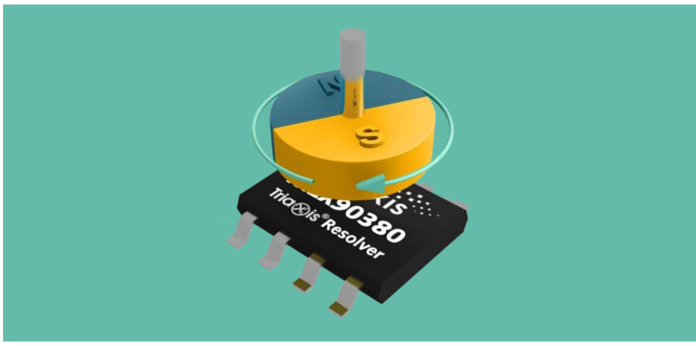

Figure 11: X/Y magnetic axis

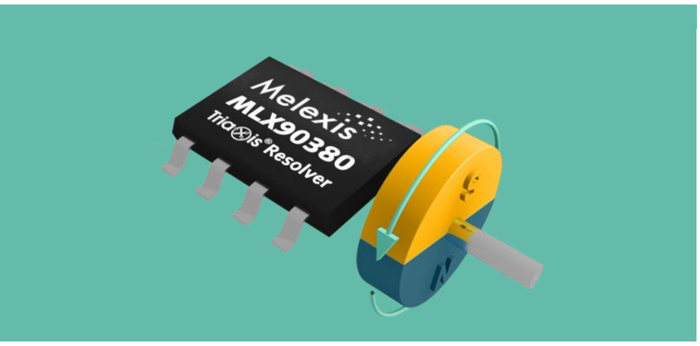

Figure 12: Z/Y magnetic axis

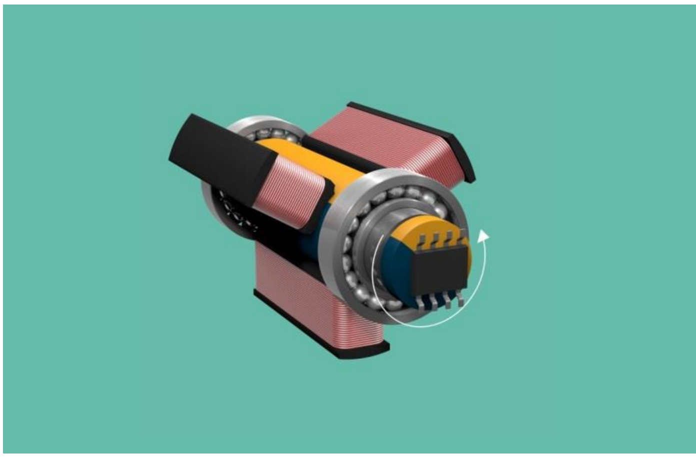

Figure 13: End of Shaft

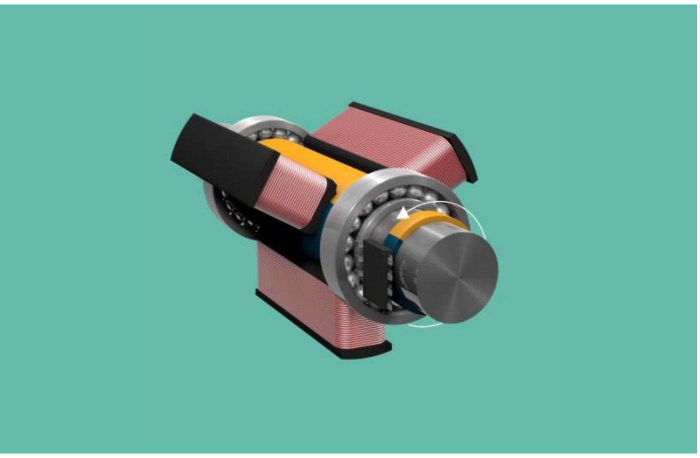

Figure 14: Trough Shaft

This feature brings a large flexibility in the positioning of the sensor versus the magnet (rotor or sensing magnet).

OUT1 and OUT2 (Sine and Cosine signal) of the sensor can be configured in X/Y magnetic axis, X/Z magnetic axis or Z/Y magnetic axis for End Of Shaft sensing and Through Shaft sensing. Through Shaft and Off-axis are used in this document as synonym. The sensors are available in a single die SOIC8 package, dual die TSSOP16 package for redundancy.

MLX91204	360 Degrees Hi-Speed Rotary Position Sensor, two ratiometric analog outputs
MLX90380	Triaxis® Resolver, 360 Degree, two ratiometric analog outputs, high speed, flexible designs

4.4. Triaxis Position products for positioning

The products mentioned so far are designed for high speed. Their update frequency is expressed in µs. Melexis offers a wide range of angular position sensors at lower speeds as well. Here, low speed means an update frequency from 200us and higher.

Some motor applications have an extra control loop for positioning. Think for example a valve. Such actuator applications might run at lower speed. Or the application uses an internal gearbox to convert a high speed/low torque rotation to a low speed/high torque rotation. Due to wear in the gearbox, the 1-1 relation between rotor position and motor output shaft is lost. As such, some designs put an extra position sensor on the output shaft.

Please check out the Triaxis position home page on www.melexis.com.

MLX90365 absolute angle output by single analog output, needs end of line calibration

MLX90363 absolute angle output by SPI

MLX90393/5 individual field components –sine/cosine- by SPI, further post processing needed. MLX90393 is for consumer applications, MLX90395 is for automotive applications.

4.5. Related Actuator products

Absolute angle position sensors can be used with Melexis' small driver ICs MLX81310-MLX81315 to drive and sense the position of a smart valve for efficient cooling of the battery or engine. It is also compatible with Melexis' BLDC motor ICs MLX81205-MLX81206-MLX81207-MLX81208 to track the rotor position in smart pumps, to control the pump efficiently and dynamically with the right torque.

5. Latch and Switch

5.1. Switch point

The Hall Effect latch is a digital semiconductor device that is activated in the presence of a magnetic field. The output of a latch changes state when a magnetic field of sufficient strength and appropriate polarity is applied, that crosses the operating point threshold (Bop). The device will keep "latch" its state when the applied magnetic field is removed (0mT). The state will be releases when a magnetic field of sufficient strength of the OPPOSITE polarity is applied that crosses the release point threshold (Br p).

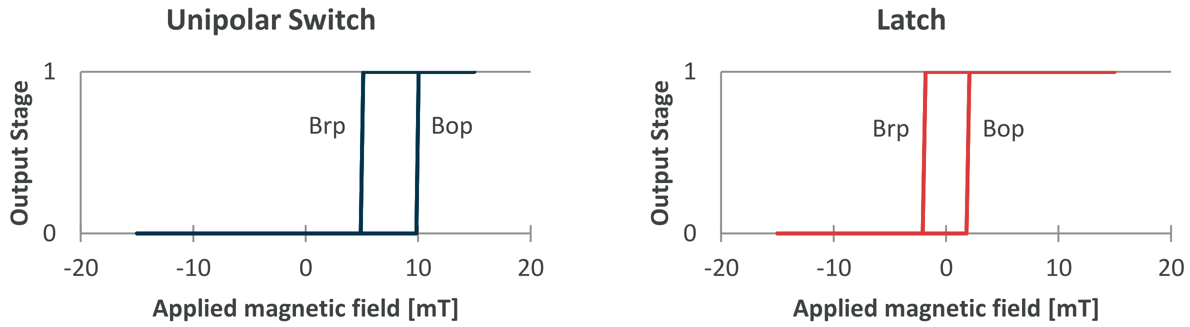

Figure 15: switching point latch and switch

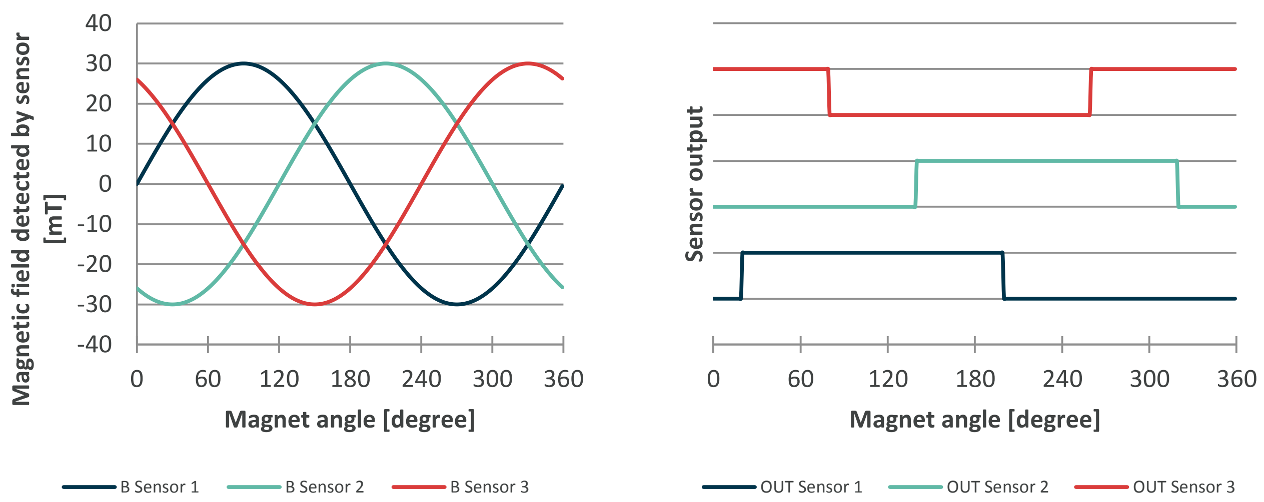

Figure 16: latch and switch sensor signals

Figure 7 how the sensors are physically positioned in the system.

The sensors in a motor commutation are used to detect the rotor position while the rotor turns. For a standard 3 phase system the sensors will generate three square wave signals with a duty cycle of 180° each shifted with 120°. These results in a switching pattern of three digital signals which generate a unique code every 60°. In other words, the three sensor signals can give a rotor position with a resolution of 60°. When the sensors are mechanically aligned correctly, the signals can be used for the communication point of the motor.

The next chapters give an overview of the typical characteristics that latch and switch sensors face in the motor commutation application.

5.2. Signal Delay

The Bop and Brp points of a switch or latch have a direct impact on the accuracy of the signal duty cycle and the magnetic angle of the switching point. The Bop level creates a trigger delay form the 0mT crossing. The relation of Brp vs. Bop determine the duty cycle of signal.

Figure 16 shows the output signals of a unipolar switch with a Bop at 10mT and a Brp at 5mT. The Bop creates a signal delay of 20°. The Brp vs. the BOP sets set the duty cycle at 150° over 360° = 41.7%.

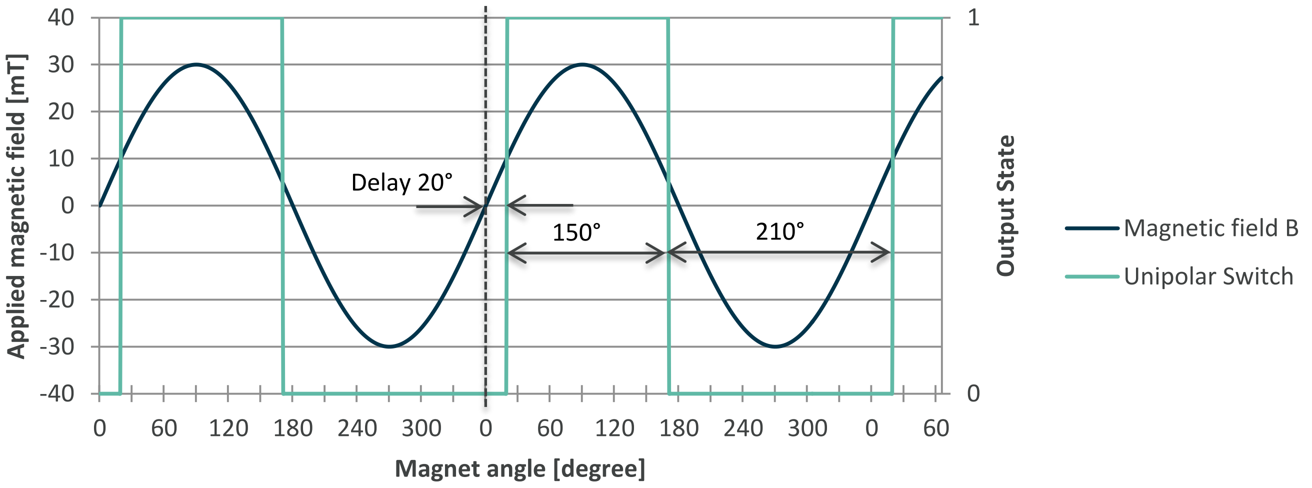

Figure 16: switch point unipolar switch

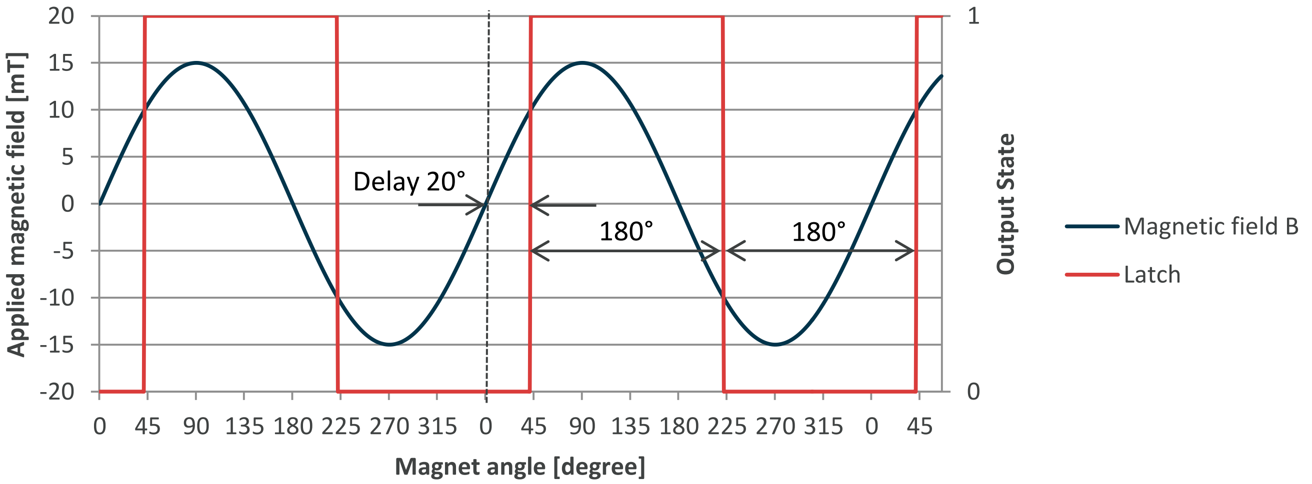

Figure 17: switch point latch

Figure 17 shows the output signals of a latch with a Bop at 10mT and a Brp at -10mT. The Bop creates a signal delay of 20°. The Brp vs. the BOP sets the duty cycle at 180° over 360° = 50%.

The new generation latches are equipped with a non-volatile memory that is used to accurately trim the switching thresholds and define the needed output magnetic characteristics (TC, Bop, Brp, Output pole functionality). In Figure 18 Bop is set to 0.5mT and Brp to -0.5mT. In this setup the signal delay is reduced to 2° with DC = 50%.

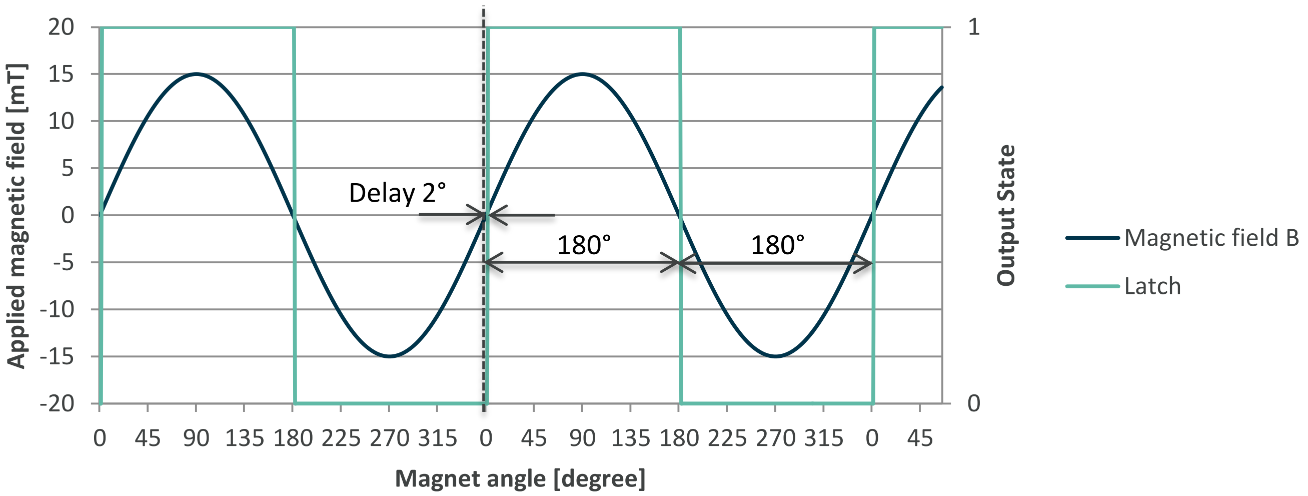

Figure 18: switch point latch

Also the sensors Refresh Period and the Output Rise/Fall Time can have an influence on the signal delay. Their significance or impact on the signal delay depends on the speed/RPM's at which the motor operates. The Output Rise/Fall Time depends on the load capacitor and pull-up resistor placed on the output of the sensor.

5.3. Bop – Brp Accuracy

The accuracy of the sensors magnetic switching points, Bop and Brp, are affected by the semiconductor manufacturing process spread. The semiconductor process spread creates a part to part variation on the sensors parameters. Important to highlight is the programmability of Melexis Latch/Switch. Melexis final test is done on 100% of the parts to absorb process variations.

Figure 19 shows the effect that the Bop and Brp tolerances have on the duty cycle of the sensor signal. For example: a typical switching point of Bop = 2mT and Brp = -2mT the duty cycle is 50%. For the minimum switching point where Bop = 0.6mT and Brp = -3.8mT, the duty cycle is ~51%. For the maximum switching point where Bop = 3.8mT and Brp = -0.6mT, the duty cycle is ~48%.

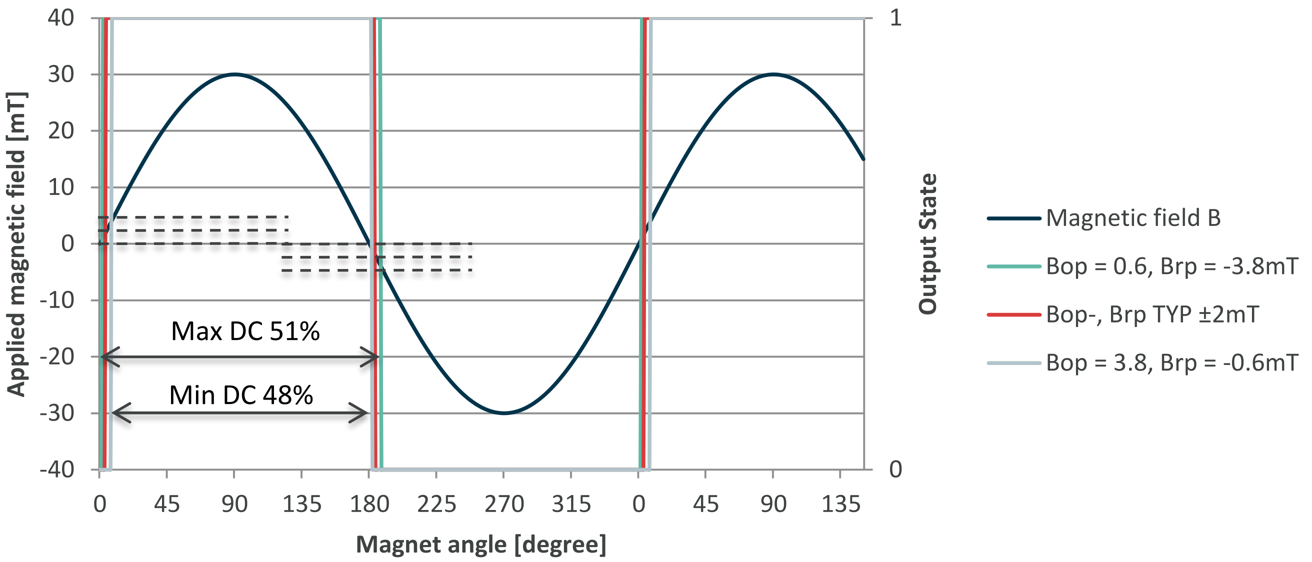

Figure 19: Bop and Brp specification

5.4. Jitter

Next to the tolerances on the Bop and Brp, there is also the jitter on the Bop and Brp points of the sensor. The jitter of the sensor is linked to the response time of the sensor. This will determine the repeatability of the switching point over time and over speed.

5.5. Temperature behavior

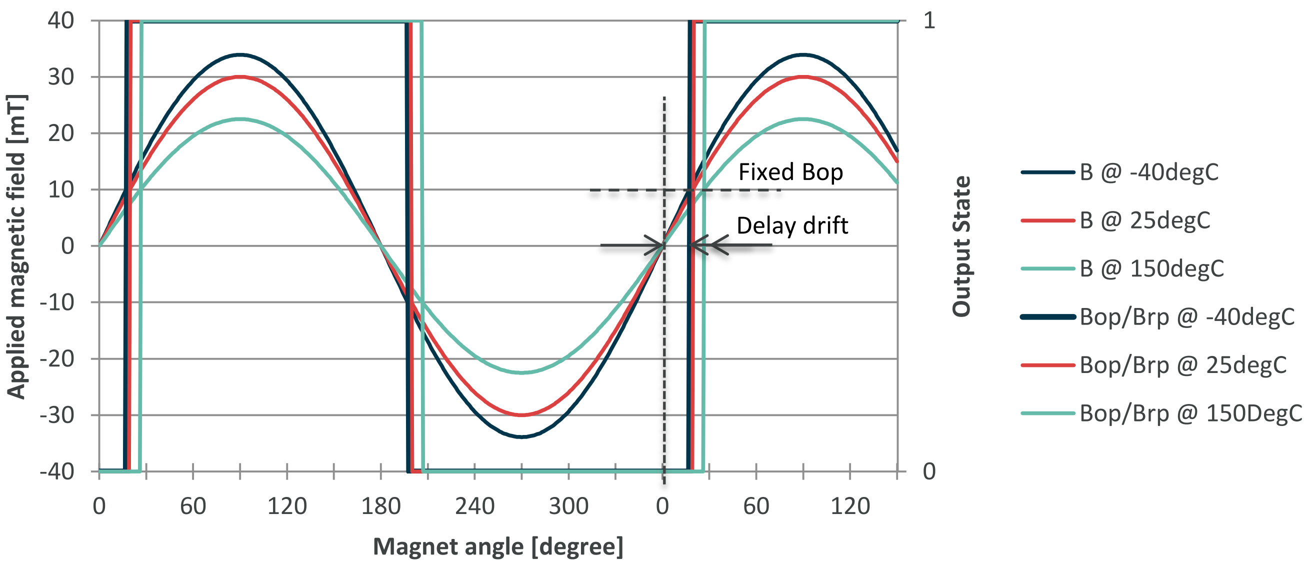

Figure 20: temperature behavior of a fixed Bop and Brp.

Melexis latch and switch sensors can compensate for thermal drift properties of the magnet.

Permanent magnets lose some of their strength over temperature and over time. The temperature effect is reproducible. Increasing temperature gives lower field, decreasing temperatures gives higher field for the same position. Because of this the amplitude of the flux density B seen by the sensor varies over time by thermal and aging effects.

Figure 20 shows the effect of temperature variations on the switching point with a fixed Bop and Brp level. As the switching point is fixed to a specific flux density, the magnetic angle at which the Bop/Brp switches will drift over temperature.

To fix this switching angle over temperature, Melexis latch and switch sensors are foreseen with a programmable Built-in Negative TC coefficient. As such, these sensors counteract the magnet's thermal drift as illustrated in Figure 21. The red curve w/TC Bop-Brp is temperature **independent.**

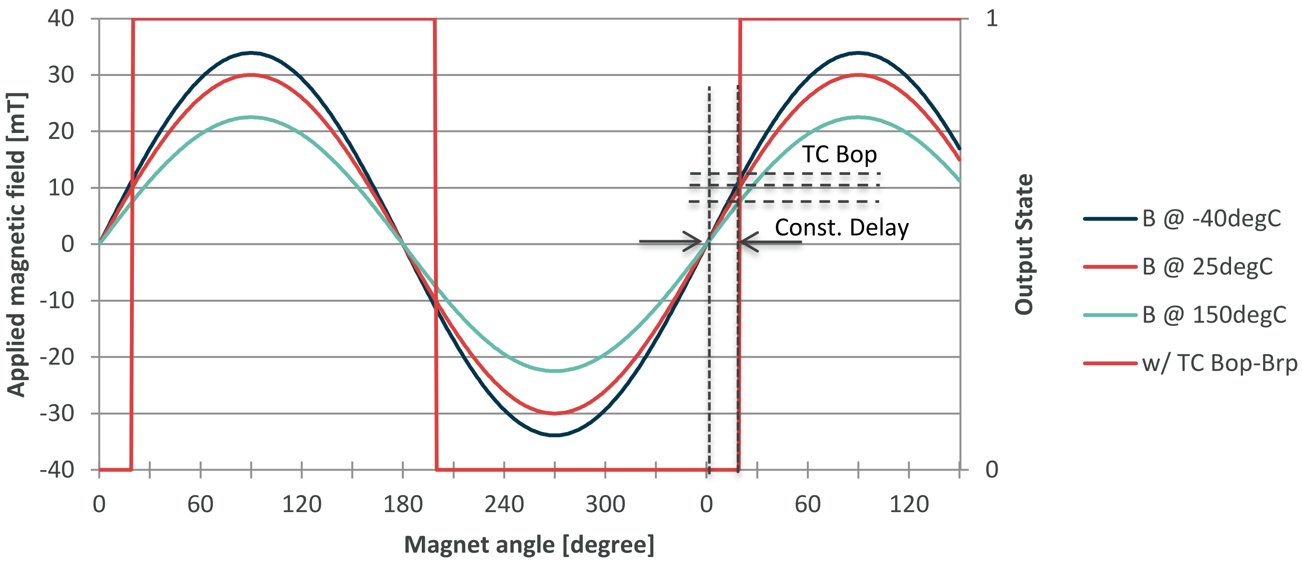

Figure 21: temperature behavior of a Bop and Brp with temperature compensation.

6. Linear

The Melexis high speed pre-programmed second generation linear Hall-effect sensor designed in mixed signal CMOS technology is an analog sensor with an output voltage proportional to the applied magnetic field and to the chip supply voltage (ratiometric). The Output Offset Level (Quiescent Level) at zero magnetic field is equal to 50% of the chip supply voltage.

A linear Hall Effect sensor can be used to replace the hall Latch sensors to detect the position of the rotor. Their analog output also makes it possible to calculate, with a dedicated algorithm, a much more accurate rotor position. This makes them not only suitable for detecting the motor commutation point but also for an accurate position control of the motor.

Two linear hall sensors placed at a 90° magnetic phase shift can also be used as a sine cosine angle sensor. The angle α is calculated from the arctangent of SIN over COS.

The resolver sensor use similar tips/tricks as this multi linear Hall Effect sensor configuration. Here, both benefit from an algorithm to absorb sensitivity and offset variations. The typical min/max algorithm can be used here. More details are mentioned in the sections below. As the linear Hall Effect sensors are used a multi-sensor configuration the positioning of the individual sensors is more crucial than on a single resolver sensor configuration. Also the part to part variations caused by the semiconductor process spread will play a part in the module performance. Although, Melexis final test on 100% of the parts will absorb most products variations. Also, note that the MLX90290 can compensate the magnet thermal drift.

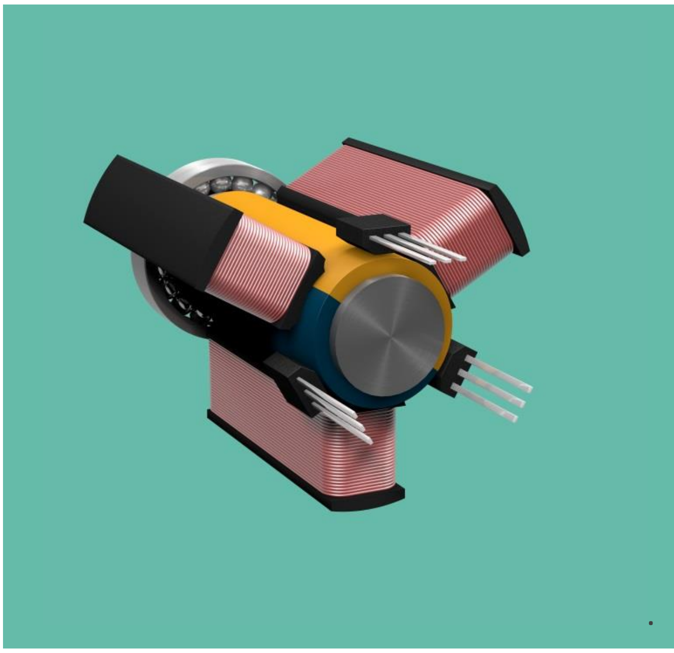

Figure 22: setup with 3 sensors

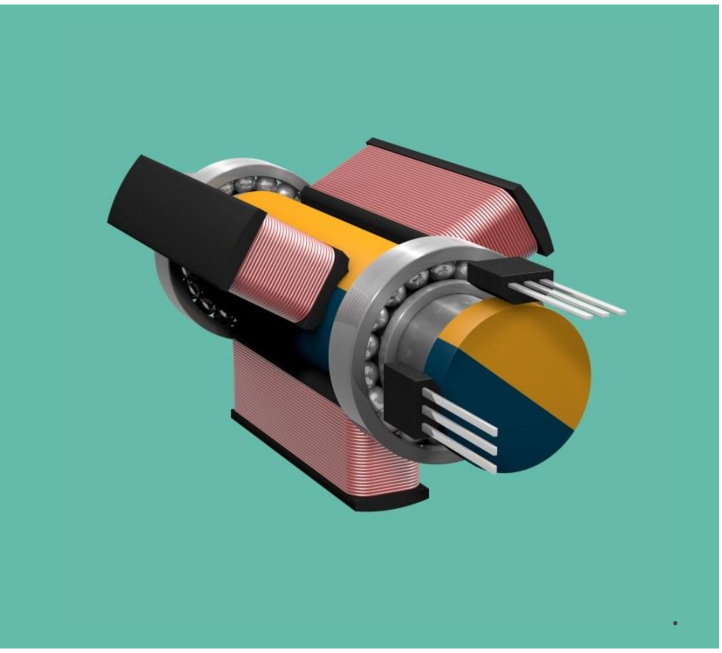

Figure 23: setup with 2 sensors

7. Resolver

The resolver sensor is a monolithic sensor IC sensitive to the flux density applied orthogonally and parallel to the IC surface. High-speed dual analog outputs allow the resolver to deliver accurate, contact-less, true 360deg sine/cosine signals when used with a rotating permanent magnet.

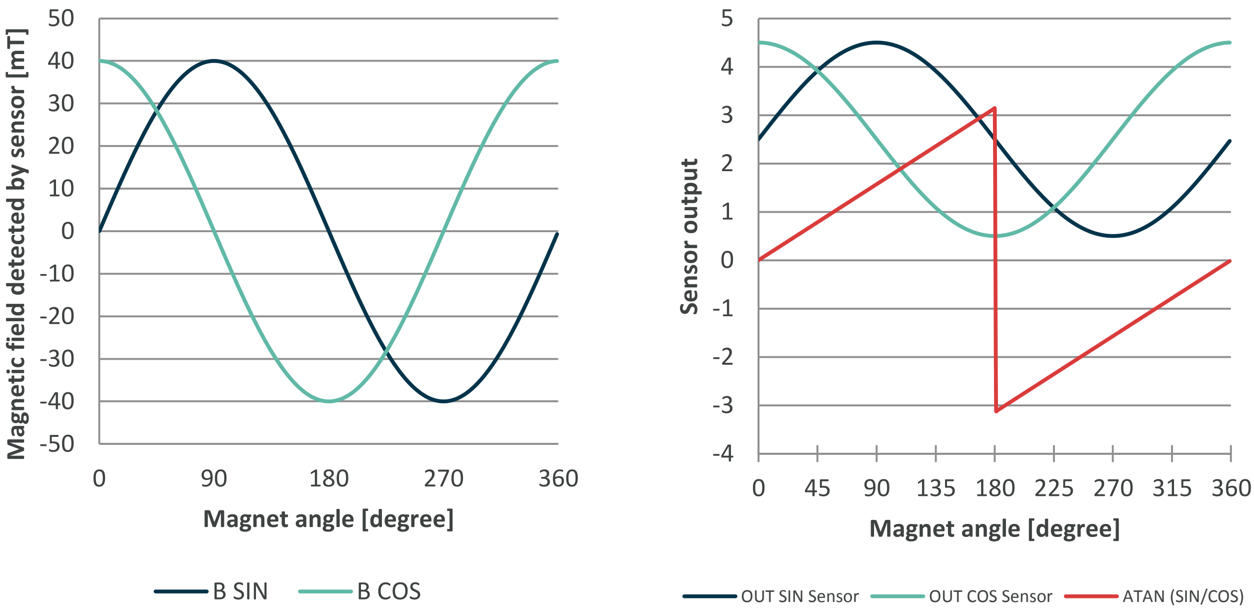

Figure 24: resolver sensor signals

In motor commutation the resolver sensor sensors are used to detect the rotor position while the rotor turns. The sensor(s) will give one full sine and cosine signal for one full 360° magnetic rotation. With the arctangent, one can calculate the angle from the sine/cosine signals.

Resolver sensors give a higher angle accuracy making them suitable for absolute motor position control. The next chapters give an overview of the typical characteristics of resolvers for motor commutation applications.

7.1. End of shaft vs. through shaft applications

Next to the temperature and aging effects of the magnet there is some non-ideal behavior of the sine and cosine signals induced by the application, magnetic construction of the application and the magnetization of the magnet. Those non ideal behaviors can be split in four main categories:

- Offset Mismatch of B_{SIN} and B_{COS};
- Sensitivity Mismatch or amplitude mismatch of B_{SIN} and B_{COS};
- Orthogonality Error or phase shift between B_{SIN} and B_{COS};
- Signal Non Linearity of the B_{SIN} and B_{COS}.

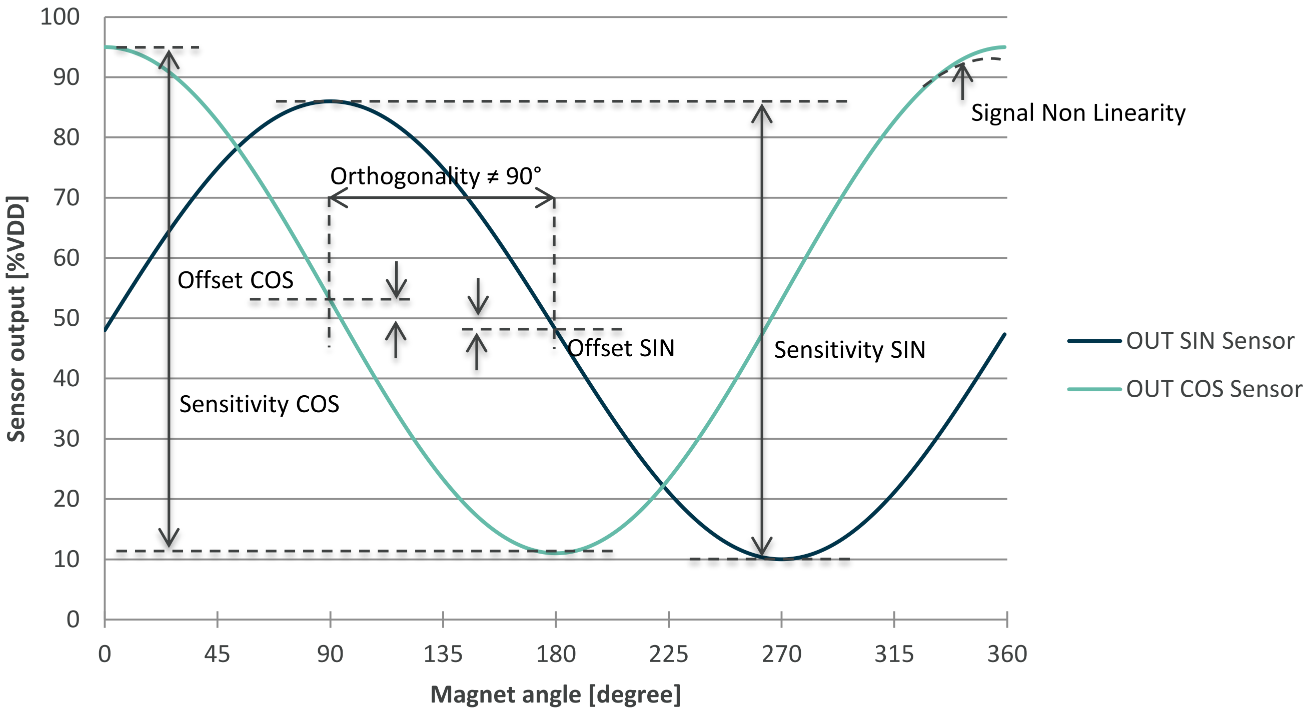

Figure 25

Figure 25 gives an overview of the four non idealities: offset drift, sensitivity drift, orthogonality drift and signal non linearity. A dynamic min-max algorithm can cancel out offset drift & sensitivity drift.

Important to note is that many of the mentioned characteristics can be compensated by a 'clever motor control algorithm'. For example, the signal delay is predictable. The motor control algorithm as such can compensate. A min-max algorithm can absorb sensitivity and offset thermal drift variations. Such min-max method adjusts offset and sensitivity of the two individual components. More detailed information on magnetic resolver IC can be found in AN_Demonstration_Evaluation_Board_MLX90380.pdf available on softdist.melexis.com

For end of shaft applications the non-ideal behaviors are relatively small as the flux density and the curve of the field lines remain fairly stable at the sensing point of the magnetic field angle while the magnet turns. “The sensor always measures the angle of the same field lines”.

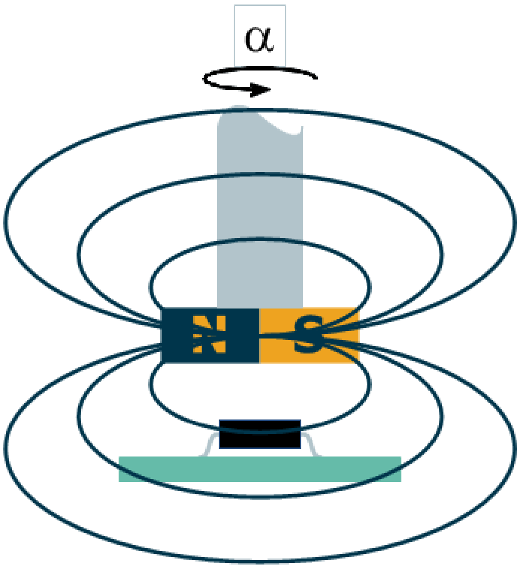

Figure 26 gives an end of shaft application.

For through shaft applications the non-ideal behaviors are larger as the variation in flux density and the curve of the field lines are larger at the sensing point of the magnetic field angle while the magnet turns. “The sensor crosses different field lines”.

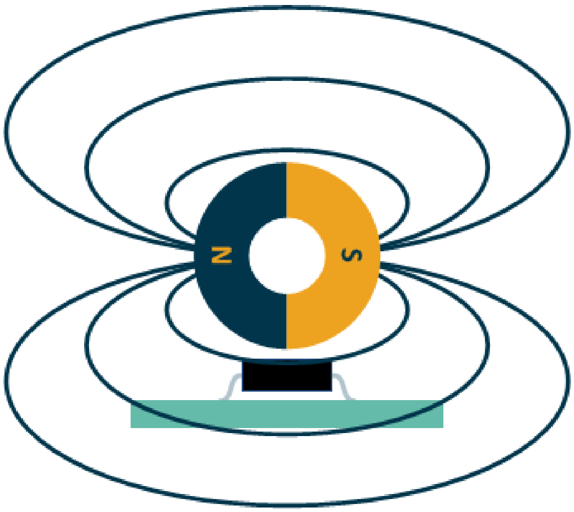

Figure 27 gives an off-axis solution

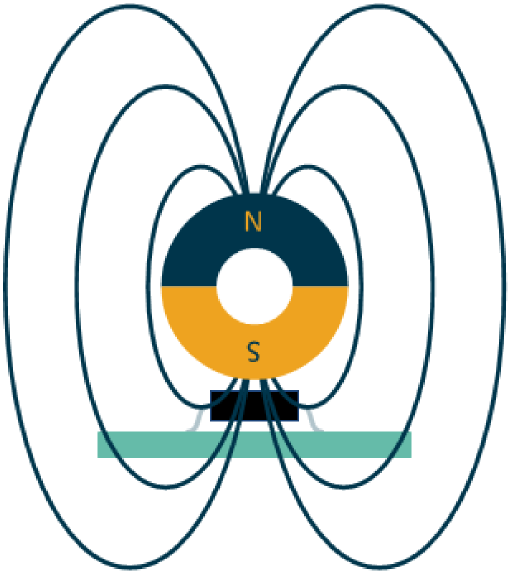

Figure 28 is the same application as Figure 32, but 90° rotation of the magnet.

For a multi-pole magnet the sensor will report for each pole pair a full magnetic rotation. The magnetization and symmetry of the magnet poles have a large influence on the symmetry of the sine and cosine signal of each magnetic rotation and therefore also on the achievable system accuracy.

7.2. Angle non-linearity correction

There are various techniques to correct the angle error of the application. For the front end calibration, the sensitivity mismatch and offset mismatch, there is the MIN-MAX method where the sensitivity and offset of the SIN and COS are normalize based on the measured amplitude of the two signals. As a back end calibration one can apply a piece wise linearization on the calculated angle by the arctangent.

For more information on the topic, please refer to the application note AN_Demonstration_Evaluation_Board_MLX90380.pdf available on softdist.melexis.com

7.3. Signal Delay

The Signal Phase Shift error or PHI is a between the $B_{COS} - B_{SIN}$ components of the magnetic field and the analog output signal, $OUT_{COS} - OUT_{SIN}$. This is phase delay is caused by the signal process time or output update rate of the sensor.

The signal process time of the sensor T_{PHI} is a constant delay expressed in µSec. The signal process time is determined by the bandwidth of the filter. The filter setting of the sensor is programmable. Note that a capacitor and series, pull-up or pull-down resistor on the output also has an influence on the signal delay.

With the filter setting programmed at high bandwidth, the sensor output update rate = 12µSec.

For a speed = 5000 $RPM = 83.3Hz$

$$1\ Revolution = \frac{1000000\mu Sec}{83.3Hz} = 12000\mu Sec$$

$$PHI = \frac{360°}{12000\mu Sec} \times 12\mu Sec = \ 0.36°$$

For a speed = 25000 $RPM = 416.6Hz$

$$1\ Revolution = \frac{1000000\mu Sec}{416.6Hz} = 2400\mu Sec$$

$$PHI = \frac{360°}{2400\mu Sec} \times 12\mu Sec = \ 1.8°$$

With the filter setting programmed at low bandwidth, the sensor output update rate = 65µSec.

For a speed = 5000 RPM

$$PHI = \frac{360°}{12000\mu Sec} \times 74\mu Sec = \ 2.22°$$

For a speed = 25000 RPM

$$PHI = \frac{360°}{2400\mu Sec} \times 74\mu Sec = \ 11.1°$$

So the signal phase shift error PHI[°] is the absolute angle offset error (Magnet angle vs. Sensors output angle) in function of the magnet rotation speed.

Figure 29 gives the phase shift error for Low bandwidth at 25000RPM. B SIN (blue) and B COS (red) is the magnetic field applied to the sensor by a full 360° turn of the magnet. OUT SIN Sensor (green) and OUT COS Sensor (purple) are the sensor outputs proportional to the applied magnetic field with a 65µSec delay from the sensor process time.

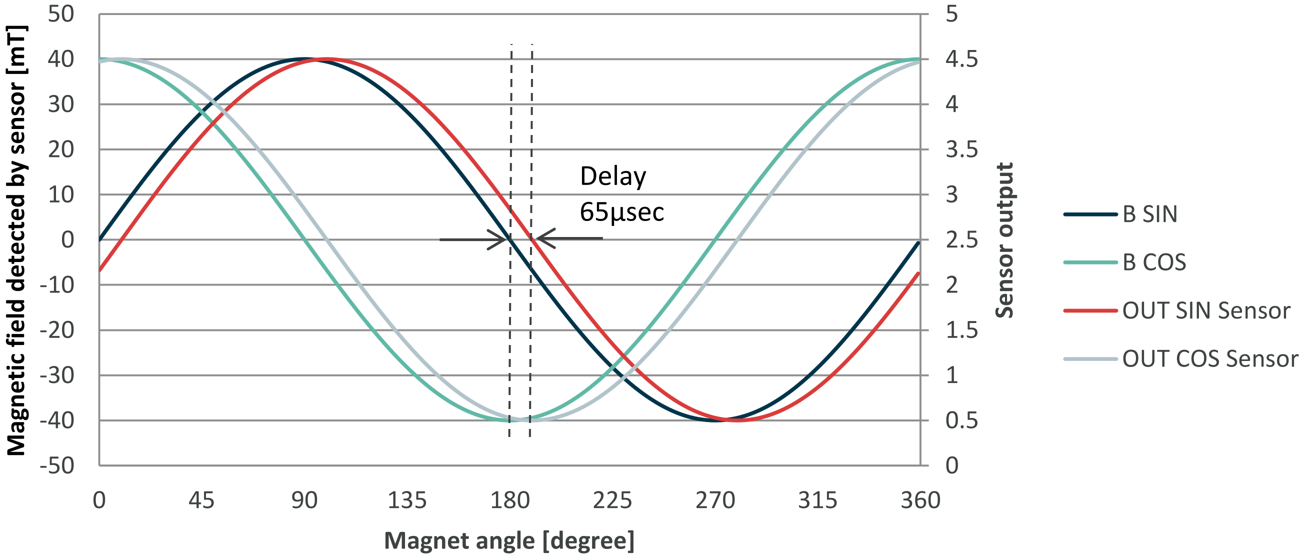

Figure 29

Important: the motor control algorithm can account for the signal delay. As such, this effect can be nullified.

7.4. Magnet thermal drift

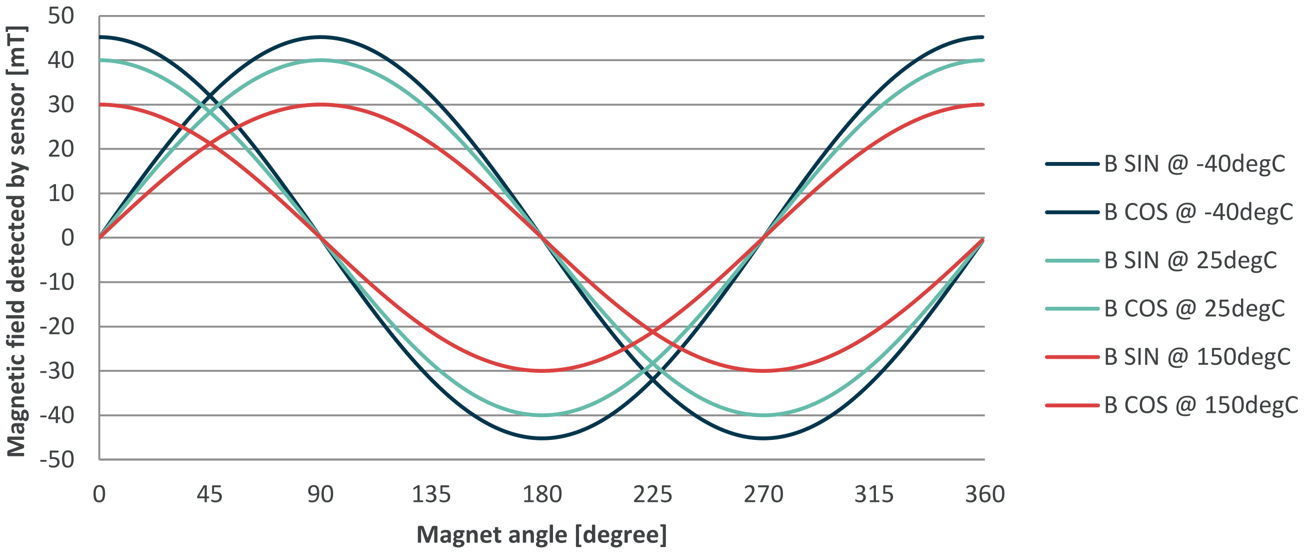

Figure 30

Permanent magnets lose some of their strength over temperature and over time. Because of this the amplitude of the flux density B sin and B cos seen by the sensor varies over time by thermal and aging effects. As the OUT_1 and OUT_2 output voltages are proportional to the applied magnetic field, also the sensor outputs will vary over time by thermal and aging effects of the magnet.

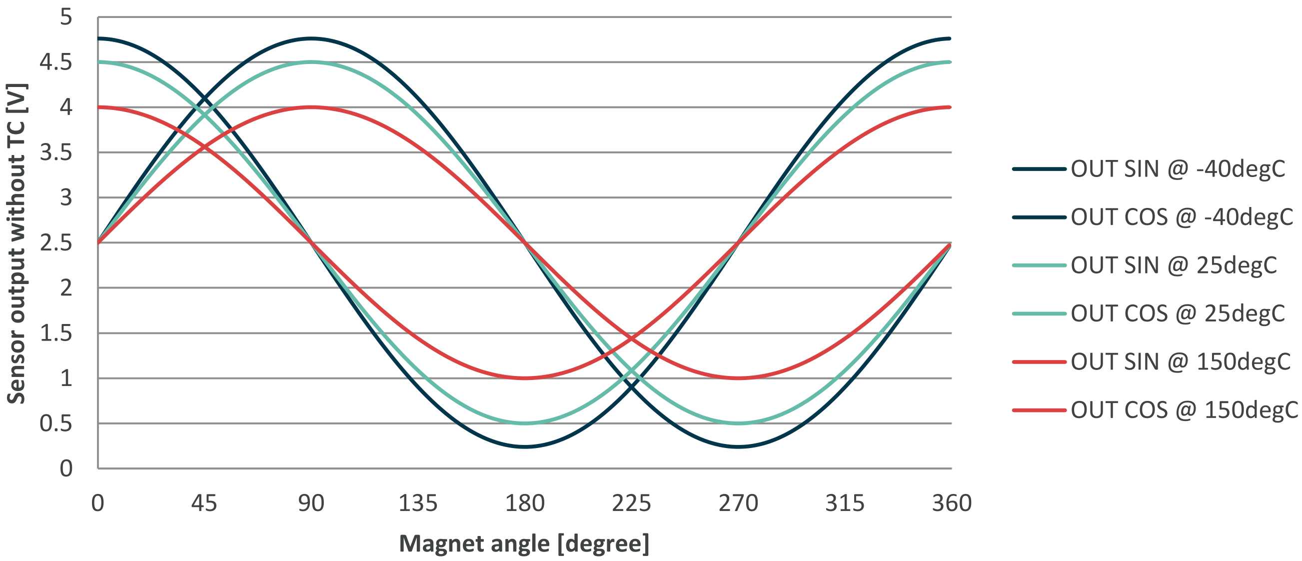

Figure 31

Figure 31 gives the resolver output signal over temperature. Increasing temperature gives lower field strength and thus lower signal amplitudes. The latest Melexis products (latch/switch, linear and resolver) have internal magnet compensation. This is not shown in this figure. For applications with linear hall or resolver, the benefit is the 'raw' sine & cosine signal have an as-big-as-possible output, maximizing readout resolution.

The angle α is calculated from the arctangent of SIN over COS:

$$\alpha = \arctan\left(\frac{B_{SIN}}{B_{COS}}\right) \text{ or } \alpha = \arctan\left(\frac{OUT_{SIN}}{OUT_{COS}}\right)$$

This feature thus has improved thermal accuracy. The arctangent operation is performed on the ratio of OUT_{SIN}/OUT_{COS}. Thus, the angular information is intrinsically self-compensated vs. flux density variations, thermal or ageing effects, affecting both signals.

The resolver sensors with their sine/cosine signals on a single sensor have the greatest benefit from this feature. For rotary position sensor based on linear Hall sensors, the part to part variations caused by the semiconductor process spread will play a part in the performance improvement.

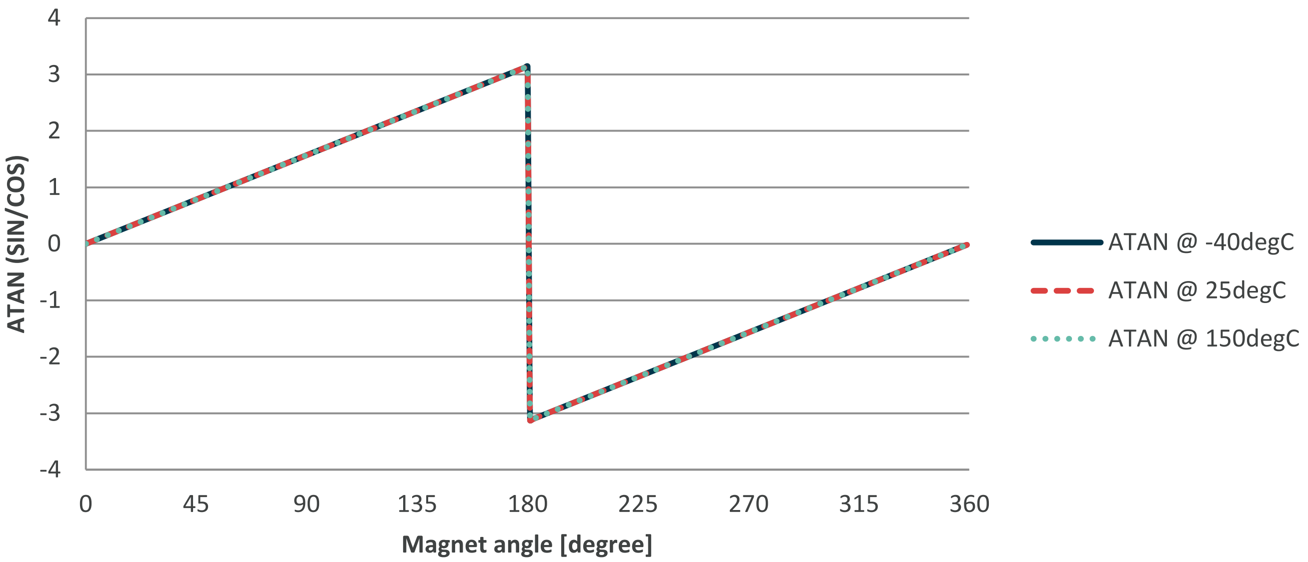

Figure 32 gives an angle output independent from temperature.

Two closing remarks: First, all latest Melexis products enable magnet thermal drift compensations. As such, they ensure the analog output signal span is as big as possible, maintaining as much resolution as possible for the readout circuit. Second, the control algorithm should apply for linear hall and resolver the min-max algorithm of AN_Demonstration_Evaluation_Board_MLX90380.pdf.

8. Conclusion

Melexis offers a complete portfolio to determine the motor position by magnetic sensing. Having such angle information can enable efficient and safe motor control algorithms for brushless motors. Having the angle position might even be interesting for actuators driving systems requiring accurate position, e.g. valves. Section 3 makes the link between motor design and possible magnetic readouts solutions. Section 4 gives an overview of the Melexis solutions. The subsequent sections explain in more detail the individual readout circuits.

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