TLE5xxx(D) Calibration 360°

GMR/TMR-based Analog Angle Sensor

About this document

Scope and purpose

This document describes the calibration algorithm and the correct implementation for GMR/TMR-based analog angle sensors TLE5xxx(D) with a measurement range of 360°. The two methods of one-point calibration (end-of-line) and ongoing calibration are presented. The document is valid for the following products:

- TLE5009
- TLE5009A16(D)
- TLE5309D (GMR Sensor Die only)
- TLE550x

Intended audience

This document is aimed at users in need of additional information regarding TLE5xxx(D) sensors.

Table of contents

1 Calibration parameters and process

The TLE5xxx(D) is an angle sensor with analog outputs. It detects the orientation of a magnetic field by measuring SIN and COS components with Giant Magneto Resistive (GMR) elements or Tunnel Magneto Resistive (TMR) elements. It provides analog SIN and COS output voltages that describe the magnet angle in a range of 0° to 360°.

Angle sensor parameters

The TLE5xxx(D) provides 4 single-ended signals SIN_N, SIN_P, COS_N and COS_P, which are centered at the voltage offset of 1.65 V for 3.3 V derivatives (GMR based sensors) or 2.5 V for 5 V derivatives (GMR based sensors) or VDD/2 for ratiometric output (TMR based sensors). The differential signals are calculated from the single-ended signals. The output voltages for Y(SIN) and X(COS) signals are expressed by ***Equation 1***. The equation is valid for single-ended mode and differential mode.

$$X = A_X \times \cos(\alpha + \phi_X) + O_X$$
$$Y = A_Y \times \sin(\alpha + \phi_Y) + O_Y$$

Equation 1

A_X Amplitude of X(COS) signal

A_Y Amplitude of Y(SIN) signal

O_X Offset of X(COS) signal

O_Y Offset of Y(SIN) signal

ϕ_X Phase of X(COS) signal

ϕ_Y Phase of Y(SIN) signal

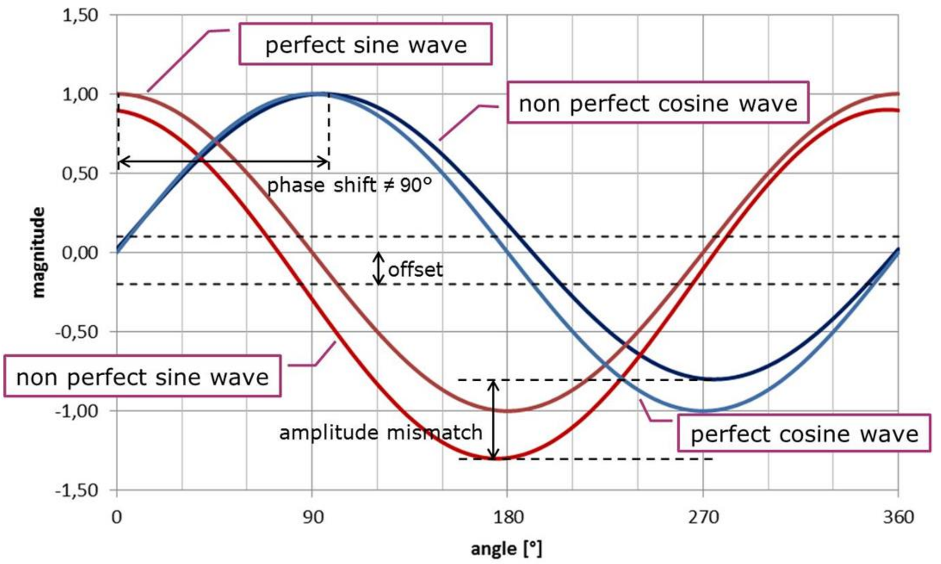

Figure 1 Differential output signals of TLE5xxx(D) with characteristic parameters; 3.3 V derivative used

The angle calculation is made with the Y(SIN) and X(COS) output signals through ***Equation 2***.

$$\alpha = \arctan\left(\frac{Y}{X}\right)$$

Equation 2

It is also possible to calculate the angle with the positive or negative single-ended output signals of the TLE5xxx(D) sensor. This may result in a reduced accuracy. Therefore it is recommended to use the sensor in differential output mode. The positive output signals of SIN and COS with the significant parameters are displayed in ***Figure 1***.

The three parameters that result in an incorrect angle calculation are the amplitude, the offset, and the non-orthogonality, which is the phase difference of X(COS) signal and Y(SIN) signal.

Calibration process

The parameters which affect the angle calculation are:

1. Offset
2. Amplitude
3. Non-orthogonality

Figure 2 displays the uncalibrated output of X and Y signals in differential mode for a 5 V derivative. The scale in the figure has been exaggerated to make the signals easier to see.

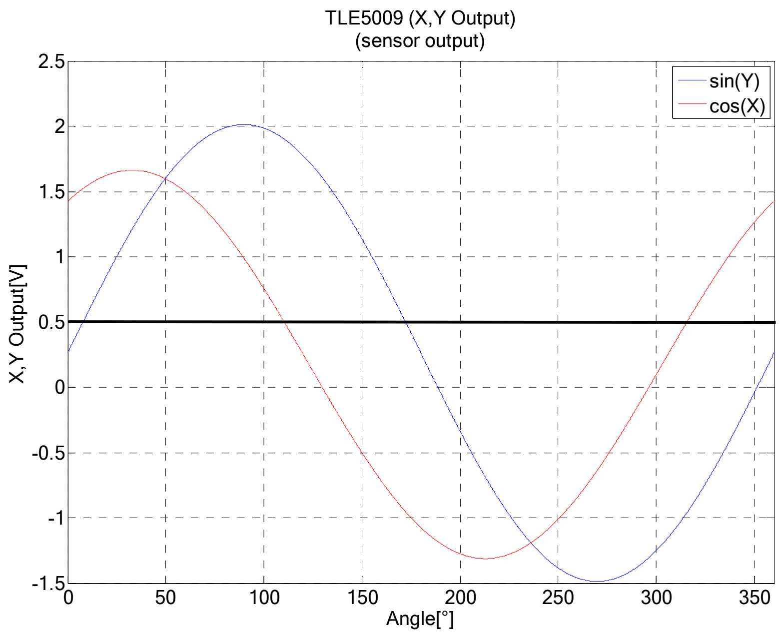

Figure 2 X(COS) and Y(SIN) output signals in differential mode for a 5 V derivative (sensor output without calibration)

The direct-angle calculation without calibration (***Equation 2***) will result in increased angle errors.

Therefore some corrections are necessary. First the offset has to be corrected (***Figure 3***).

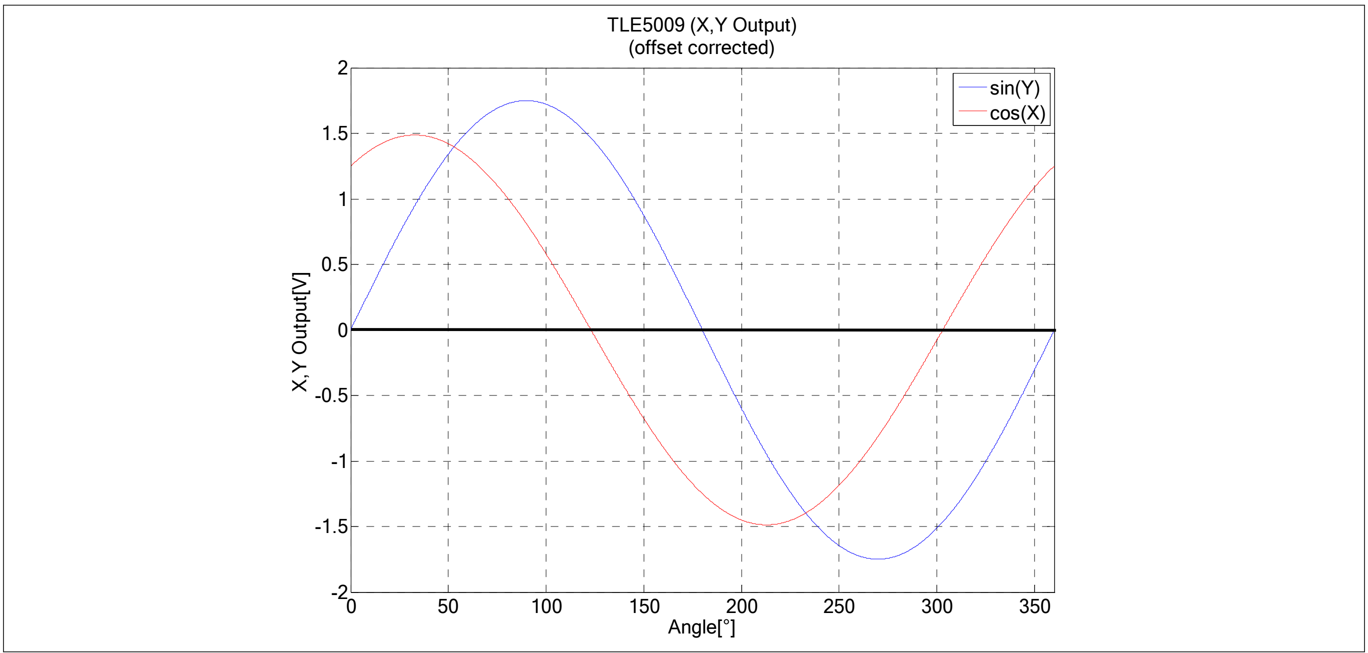

Figure 3 X(COS) and Y(SIN) output signals in differential mode for a 5 V derivative (offset corrected)

The next step is the amplitude normalization (***Figure 4***), followed by the correction of the non-orthogonality.

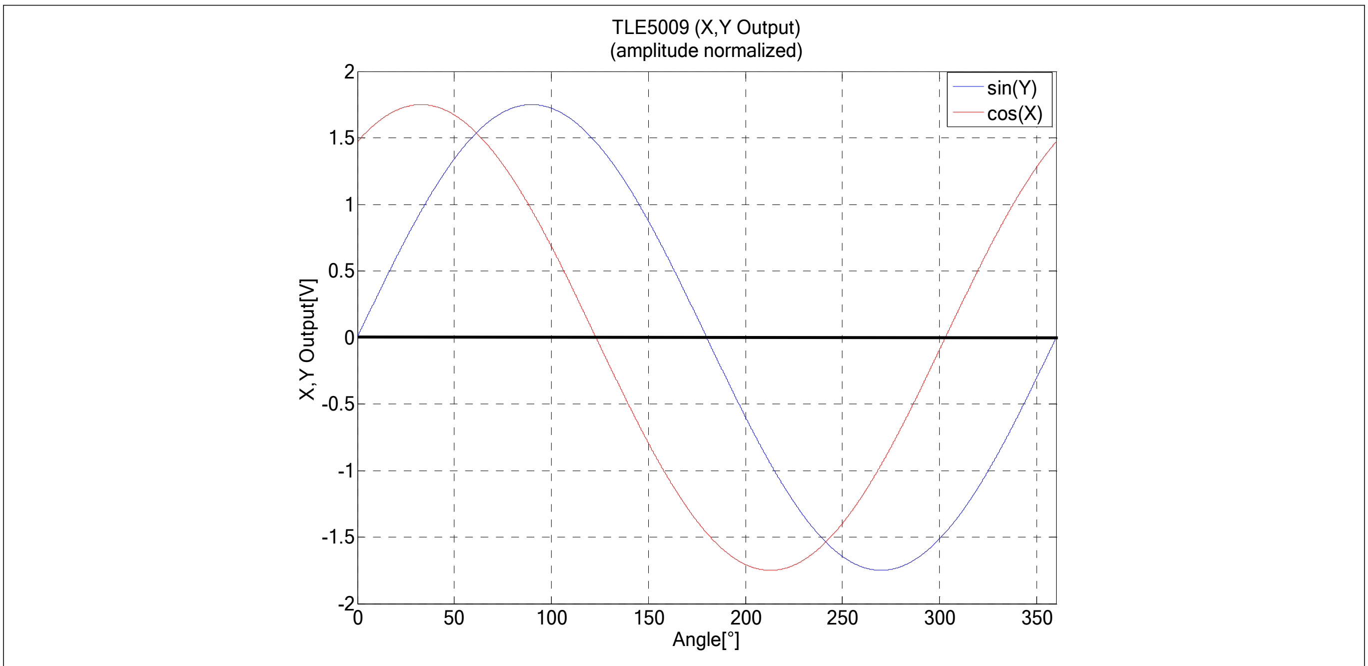

Figure 4 X(COS) and Y(SIN) output signals in differential mode for a 5 V derivative (offset corrected and amplitude normalized)

By applying these corrections, the angle error is minimized. Ideally, the X(COS) and Y(SIN) signals have no offset. They have the same amplitude and are phase-shifted by 90° in relation to each other.

2 Calibration of TLE5xxx(D)

This chapter explains how to determine the angle sensor calibration parameters such as amplitude, offset, and non-orthogonality of X and Y channels for one-point (end-of-line) and ongoing (continuous) calibration.

Note: All Min/Max values have to be measured at the same temperature. Otherwise, incorrect calibration data would result.

2.1 One-point calibration (end-of-line)

The one-point calibration can be carried out end-of-line with the advantage of the calibration of the hysteresis effect due to a counterclockwise and clockwise measurement. The end-of-line calibration can be accomplished using the following sequence (***Figure 5***):

1. Turn magnetic field 360° **left** and measure X and Y values
2. Calculate amplitude, offset, non-orthogonality correction values of left turn
3. Turn further 90° left and 90° back right without measurement: calibration of hysteresis
4. Turn magnetic field 360° **right** and measure X and Y values
5. Calculate amplitude, offset, non-orthogonality correction values of right turn
6. Calculate mean values of amplitude, offset, non-orthogonality correction

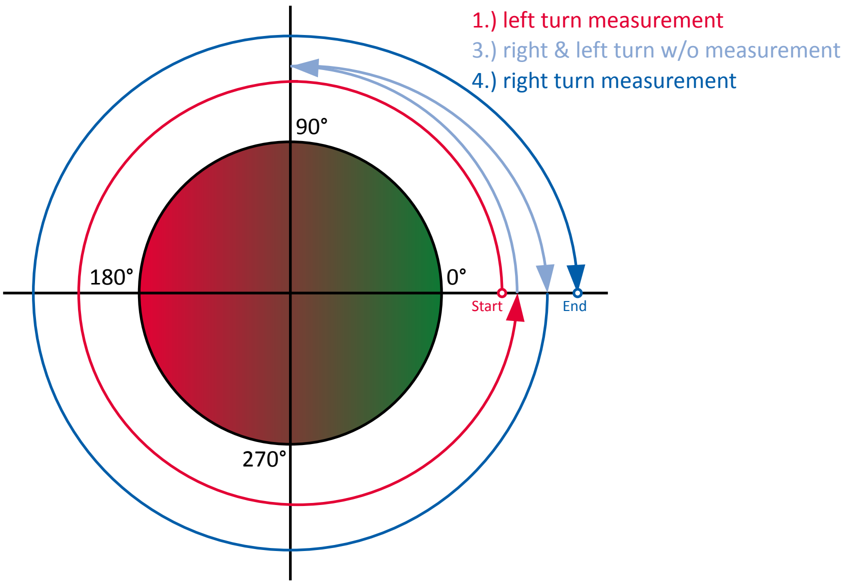

Figure 5 Calibration routine with Min-Max method

The calibration must be performed with a magnet in the specified magnetic field range and is normally carried out at room temperature.

2.2 Ongoing calibration

Calibration should be performed continuously in every full turn measurement in order to achieve a high angle accuracy. This method is suitable for one-way rotation applications. There are two methods for extracting the calibration parameters:

1. Min-Max method with
   a. Direct orthogonality error calculation: this method is suitable when only minor measurement errors are expected
   b. Enhanced orthogonality error calculation: this method is suitable for expected high measurement deviations
2. Exact method with DFT

The Min-Max method with direct orthogonality error calculation can be used for most applications. If parameter measurement deviations of more than 5° are expected, the enhanced orthogonality error calculation should be used for the Min-Max method. Another option is the extraction of the parameters with the Discrete Fourier Transformation.

2.2.1 Min-Max method with direct orthogonality calibration

With the Min-Max method, amplitude, offset and non-orthogonality can be determined for a correct calibration of the TLE5xxx(D) sensor. The values at minimum and maximum SIN and COS are used to calculate the compensation parameters.

X_{max}, X_{min}, Y_{max} and Y_{min} have to be extracted out of every measurement (***Figure 6***). At least one full turn is required, but it is recommended to find the minimum and maximum values from two full turn measurements.

Note: All Min/Max-values have to be measured at the same temperature. Otherwise, incorrect calibration data would result.

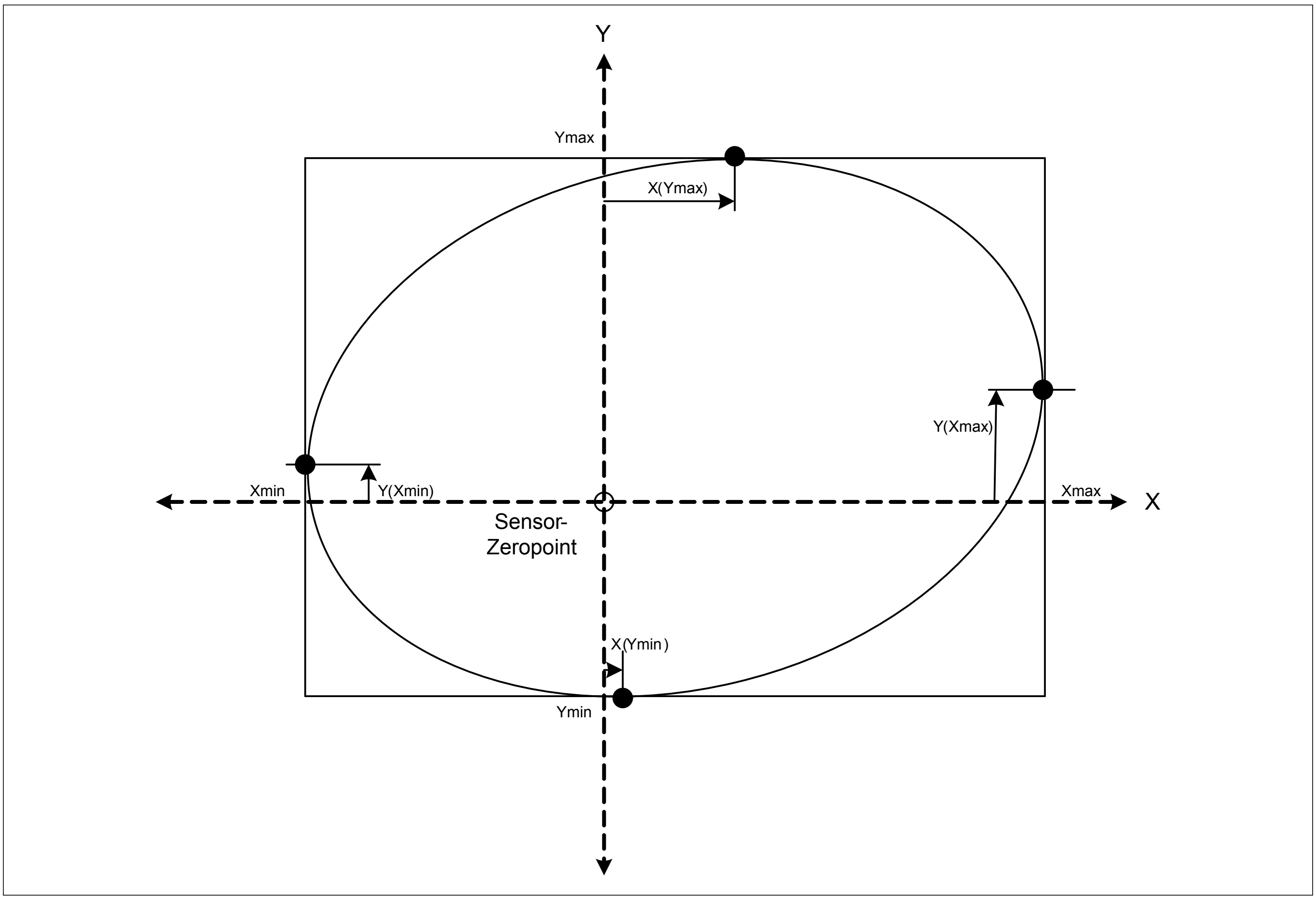

Figure 6 Min-Max method

Step 1: Calculate the amplitude and offset

The amplitude (***Equation 3***, ***Equation 4***) and the offset (***Equation 5***, ***Equation 6***) can be calculated with the measured data:

$$A_X = \frac{X_{max} - X_{min}}{2}$$

Equation 3

$$A_Y = \frac{Y_{max} - Y_{min}}{2}$$

Equation 4

$$O_X = \frac{X_{max} + X_{min}}{2}$$

Equation 5

$$O_Y = \frac{Y_{max} + Y_{min}}{2}$$

Equation 6

Step 2: Correct for offset and normalize

Correct the raw values of X(COS) and Y(SIN) by subtracting the offset which was calculated in ***Equation 5*** and ***Equation 6***:

$$X_1 = X - O_X$$
$$Y_1 = Y - O_Y$$

Equation 7

Further normalize the X_1 and Y_1 values by using the mean values calculated in ***Equation 3*** and ***Equation 4***:

$$X_2 = \frac{X_1}{A_X}$$
$$Y_2 = \frac{Y_1}{A_Y}$$

Equation 8

X_2 and Y_2 are offset and amplitude-corrected raw signals of COS and SIN.

Step 3: Calculate the vector length

The corresponding maximum and zero-crossing points of the SIN and COS signals do not occur at the precise distance of 90°. The difference between X(COS) and Y(SIN) phases from ***Equation 1*** express the orthogonality error ϕ.

$$\phi = \phi_X - \phi_Y$$

Equation 9

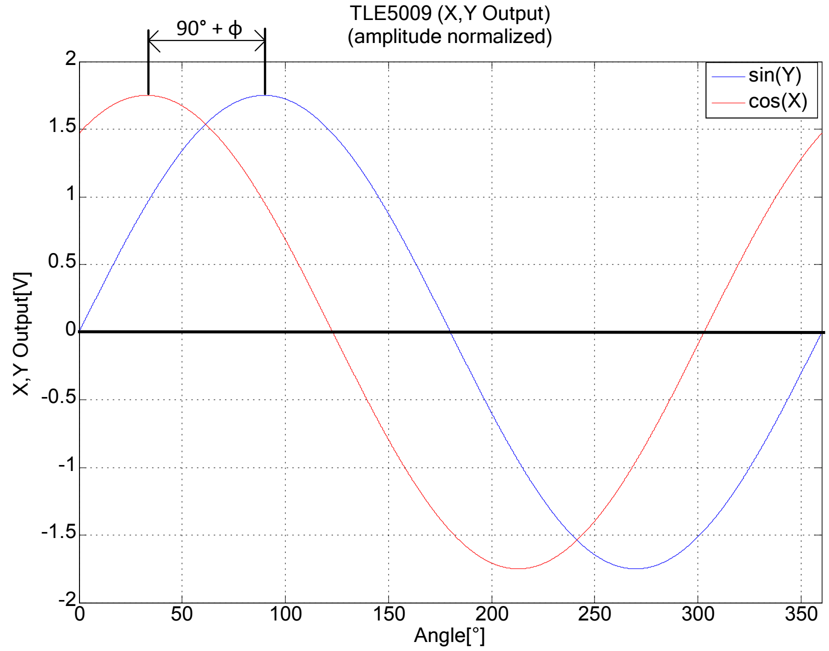

Figure 7 Orthogonality error

The orthogonality can be calculated from the magnitude of two 90° angle shifted components. Possible angle combinations are 45° and 135°, 135° and 225°, 225° and 315° or 315° and 45°.

The angle value is provided by the angle sensor. No reference is necessary.

At an angle output of 45° the corresponding Y(SIN) and X(COS) values can be read out. This is also the case at 135°.

The length of magnitude at 45° and 135° can be calculated from the X_2 and Y_2 components resulting in the calculated values for 45° and 135°:

$$M_{45} = \sqrt{X_{2(45)}^{2} + Y_{2(45)}^{2}}$$
$$M_{135} = \sqrt{X_{2(135)}^{2} + Y_{2(135)}^{2}}$$

Equation 10

M_{45}, M_{135}	Magnitude at 45° and 135° for X2, Y2
X_{45}, X_{135}	COS values at 45° and 135° for X2, Y2
Y_{45}, Y_{135}	SIN values at 45° and 135° for X2, Y2

Step 4: Non-orthogonality calculation

The length of magnitude at 45° and 135° can now be used to determine the non-orthogonality.

$$\phi = 2 * \arctan\left(\frac{M_{135} - M_{45}}{M_{135} + M_{45}}\right)$$

Equation 11

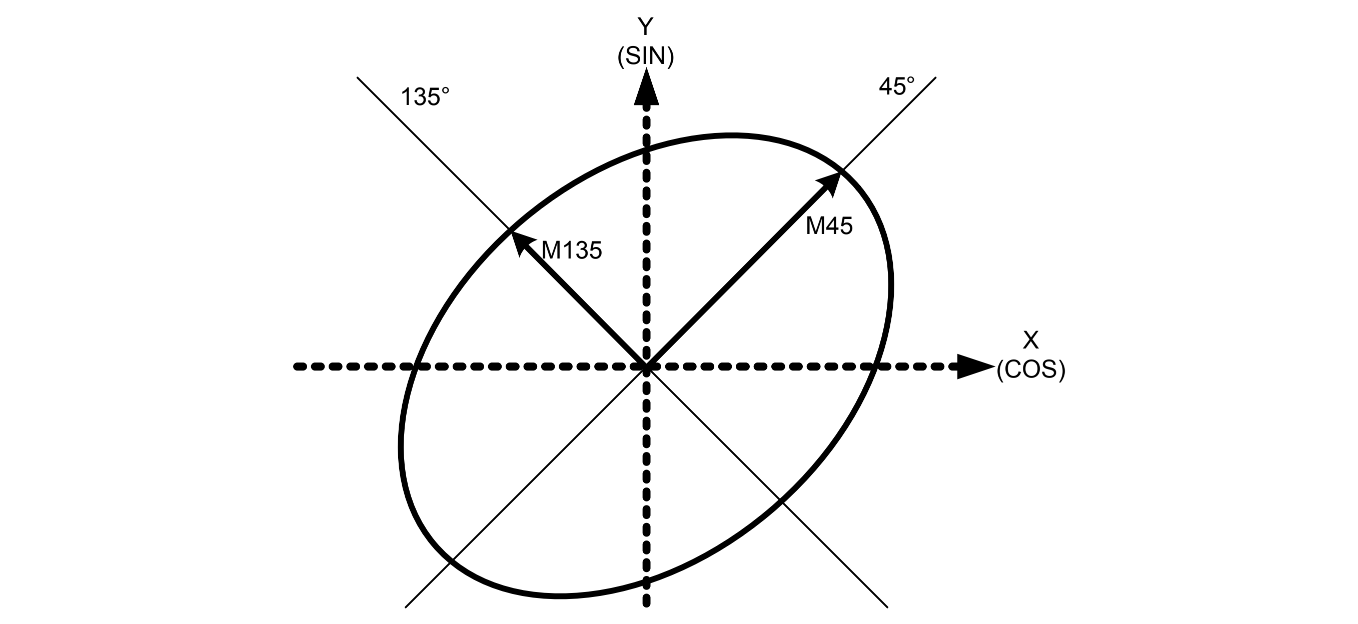

Figure 8 Correction of orthogonality error

For an ongoing calibration, the non-orthogonality should be calculated for each turn. For calibration at the same temperature condition, the non-orthogonality is expected to have a small drift. Therefore, the non-orthogonality from the prior calculation can be applied for the current calibration. This is only necessary for the Y component. The X channel represents the reference and is not necessarily aligned with 0° of the system in which the sensor is used.

$$Y_3 = \frac{Y_2 - X_2 * \sin(-\phi)}{\cos(-\phi)}$$

Equation 12

Step 5: Final compensated angle

After correcting of all errors, the resulting angle can be calculated using the arctan function [1)] with the Y_3 orthogonality compensated value and the normalized value of X_2.

$$\alpha = \arctan\left(\frac{Y_3}{X_2}\right)$$

Equation 13

2.2.2 Min-Max method with enhanced orthogonality calibration

The Min-Max method mentioned in the previous chapter uses the vector length at two 90° shifted angle components to calculate the orthogonality error, for example at 45° and 135°. The sensor output values used for the vector length calculation are still uncalibrated with including non-orthogonality. It is possible that a measurement which is expected at e.g. 45° is performed at e.g. 38°. For deviations of more than 5° in the measurement accuracy, the calculation of the non-orthogonality mismatch increases. We are therefore introducing a new algorithm for calculating the orthogonality error which is more stable in erroneous measurement conditions.

1 Microcontroller library function $\arctan2(Y_3, X_2)$ works better to resolve 360°

Non-orthogonality calculation with expected exact measurement values

The non-orthogonality describes the phase difference of SIN and COS signals from the exact distance of 90°. In the previous chapter the algorithm to calculate the orthogonality error expects almost exact measurement values. The sensor output values (X_{45}, Y_{45}) and (X_{135}, Y_{135}) are read out at 45° and 135°. It is possible for the 90° orthogonality correlation to be misaligned in the measurement and the desired points may be missed by 10° or more, e.g. 38° and 140°. With this algorithm, an increased error will occur which is shown in ***Figure 9***.

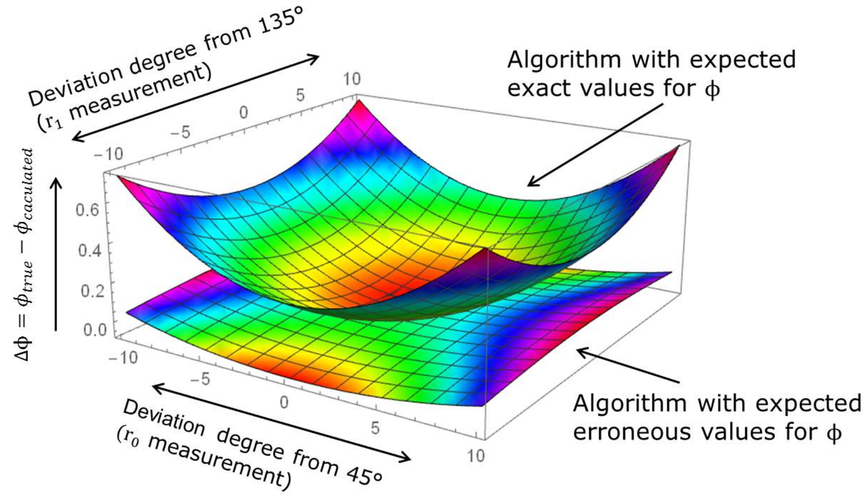

Figure 9 Simulation of orthogonality error dependent on misaligned measurement conditions with direct orthogonality (expected exact values) and enhanced orthogonality (expected erroneous values) calculation (r_0: vector length at 45°; r_1: vector length at 135°)

The simulation shows very good results for deviations up to 5°, but a further increase results in a higher orthogonality error calculated with the algorithm which expects the exact values for ϕ.

Non-orthogonality calculation with expected erroneous measurement values

This optimized orthogonality error calculation is highly immune to erroneous measurement points which is shown in ***Figure 9***. It can also be used for high speed applications and enables simultaneous calibration. Step 3 and step 4 differ from the Min-Max method in chapter ***Min-Max method with direct orthogonality calibration***.

After step 1 and step 2, which normalize the amplitude and calculate amplitude and offset, the vector length is also necessary in different form:

$$M_{45}^2 = X_{2(45)}{}^2 + Y_{2(45)}{}^2$$
$$M_{135}^2 = X_{2(135)}{}^2 + Y_{2(135)}{}^2$$

Equation 14

Additionally a parameter Δr^2 is introduced to check the correct measurement at the expected position, which is defined as:

$$\Delta r^2 = \left(\arctan\left(\frac{Y_{2(45)}}{X_{2(45)}}\right) - \frac{\pi}{4}\right)^2 + \left(\arctan\left(\frac{Y_{2(135)}}{X_{2(135)}}\right) - \frac{3\pi}{4}\right)^2$$

Equation 15

With this parameter and a trigonometric conversion of $\phi = 2 * \arctan\left(\frac{M_{135} - M_{45}}{M_{135} + M_{45}}\right)$ it is possible to achieve an optimized angle calculation through:

$$\phi_{Opt} = \frac{\phi}{1 - \Delta r^2}$$

$$\phi_{Opt} = \frac{2 * \arctan\left(\frac{M_{135} - M_{45}}{M_{135} + M_{45}}\right)}{1 - \Delta r^2} = \frac{\arcsin\left(\frac{M_{135}^2 - M_{45}^2}{M_{135}^2 + M_{45}^2}\right)}{1 - \Delta r^2}$$

Equation 16

where $\Delta r^2 < < 1$

Through the approximation it is possible to use this algorithm in high speed applications with a similar computation power as the orthogonality calculation algorithm which uses the arctan() function. This optimized orthogonality error calculation also delivers high accuracy for misaligned measurement points up to 10° or more. ***Figure 10*** shows the resulting angle error with these two orthogonality error calculation methods using ***Equation 11*** and ***Equation 16***. Measurement deviations of -10° for ($X_{2(45)}$, $Y_{2(45)}$) and +12° for ($X_{2(135)}$, $Y_{2(135)}$) are simulated with an orthogonality error of 10°. Both graphs calculate the final angle with the Min-Max method.

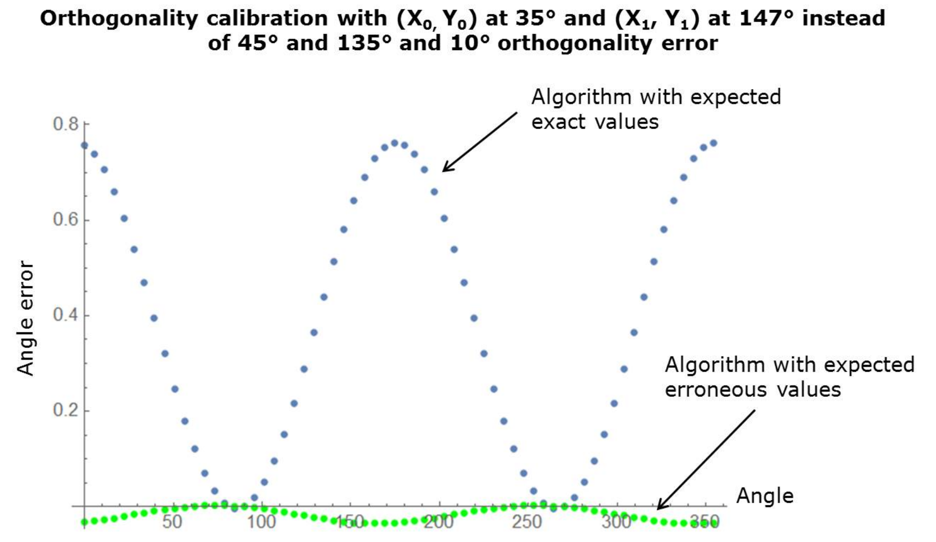

Figure 10 **Angle error compensation of ideal SIN and COS for TLE5xxx(D) sensor with direct orthogonality (expected exact values) and enhanced orthogonality (expected erroneous values) calculation**

Finally, the corrected Y component can be calculated with the orthogonality error identified:

$$Y_3 = \frac{Y_2 - X_2 * \sin(-\phi)}{\cos(-\phi)}$$

Equation 17

2.2.3 Exact method with DFT

This method uses the Discrete Fourier Transform (DFT) method to extract the parameters from the measurements. Therefore an accurate reference system is necessary. This method is done using 2^m measurement points at 360° (e.g. m = 8; $n = 2^m = 2^8 = 64$). At least one full turn is required, but it is recommended to find the values from two full turn measurements.

DFT Offset Calculation

The offset is calculated by the summation of the X or Y measurements divided by the number of measurement points (***Equation 18***):

$$O_X = [X(1) + X(2) + .. + X(n)]/n$$
$$O_Y = [Y(1) + Y(2) + .. + Y(n)]/n$$

Equation 18

X(n) X value at measurement point n

Y(n) Y value at measurement point n

n Measurement points

DFT amplitude and phase calculation

To determine the amplitude, the real and imaginary parts must be calculated. This has been done in ***Equation 19*** for the X values and ***Equation 20*** for the Y values. β describes the reference angle (e.g. n = 64; measurement every 360° / 64 = 5.625° step).

$$\text{DFT\_X\_r} = [X(1) \times \cos(\beta 1) + X(2) \times \cos(\beta 2) + \ldots + X(n) \times \cos(\beta n)] \times 2/n$$
$$\text{DFT\_X\_i} = [X(1) \times \sin(\beta 1) + X(2) \times \sin(\beta 2) + \ldots + X(n) \times \sin(\beta n)] \times 2/n$$

Equation 19

$$\text{DFT\_Y\_r} = [Y(1) \times \cos(\beta 1) + Y(2) \times \cos(\beta 2) + \ldots + Y(n) \times \cos(\beta n)] \times 2/n$$
$$\text{DFT\_Y\_i} = [Y(1) \times \sin(\beta 1) + Y(2) \times \sin(\beta 2) + \ldots + Y(n) \times \sin(\beta n)] \times 2/n$$

Equation 20

Now the amplitude and the phase can be calculated (***Equation 21***, ***Equation 22***)

$$A_X = \sqrt{(\text{DFT\_X\_r})^2 + (\text{DFT\_X\_i})^2}$$
$$A_Y = \sqrt{(\text{DFT\_Y\_r})^2 + (\text{DFT\_Y\_i})^2}$$

Equation 21

The calculation of the phase error is only necessarily for the Y component. The X channel represents the reference and is not necessary aligned with 0° of the system in which the sensor is used.

$$\varphi = \frac{\pi}{2} - \arctan\left(\frac{\text{DFT\_Y\_i}}{\text{DFT\_Y\_r}}\right)$$

Equation 22

Final parameters and angle calculation

After calculating of all parameters, the raw values of X(COS) and Y(SIN) can be corrected by subtracting the offset with ***Equation 23*** :

$$X_1 = X - O_X$$
$$Y_1 = Y - O_Y$$

Equation 23

Further normalize the X_1 and Y_1 values by using the mean values calculated in ***Equation 21***:

$$X_2 = \frac{X_1}{A_X}$$
$$Y_2 = \frac{Y_1}{A_Y}$$

Equation 24

X_2 and Y_2 are offset and amplitude-corrected raw signals of COS and SIN.

The influence of the non-orthogonality can be compensated for each measurement by using ***Equation 25***, in which only the Y channel must be corrected. The X channel represents the reference.

$$Y_3 = \frac{Y_2 - X_2 * \sin(-\phi)}{\cos(-\phi)}$$

Equation 25

After correcting of all errors, the resulting angle can be calculated using the arctan function [2)] with the Y_3 orthogonality compensated value and the normalized value of X_2.

$$\alpha = \arctan\left(\frac{Y_3}{X_2}\right)$$

Equation 26

2.3 Optional: temperature-dependent offset compensation

The TLE5xxx(D) has a temperature-dependent offset behavior. It is possible to do a temperature offset compensation to achieve more accurate angle values over the whole temperature range.

The temperature of the chip can be read out, if a diagnostic pin (V_{DIAG}) with temperature information is available. The offset values O_X and O_Y can be described by the following equations:

$$O_X = O_{X25} + \mathrm{KT}_{\mathrm{OX}} \times (T - T_{25})$$
$$O_Y = O_{Y25} + \mathrm{KT}_{\mathrm{OY}} \times (T - T_{25})$$

Equation 27

2 Microcontroller library function $\arctan2(X_3, X_2)$ works better to resolve 360°

O_{X25} Offset of X(COS) signal at room temperature

O_{Y25} Offset of Y(SIN) signal at room temperature

KT_{OX} X-Offset coefficient

KT_{OY} Y-Offset coefficient

T Temperature

T_{25} Temperature at room temperature

The temperature coefficient can be calculated from two measurements at two different temperatures (e.g. T25 and HT).

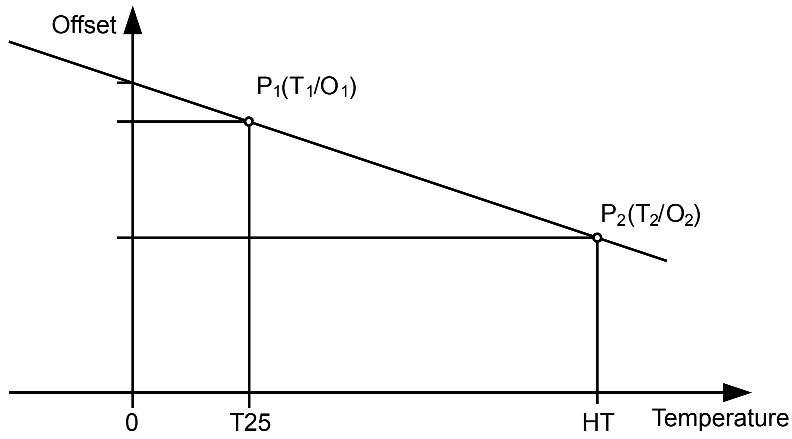

Figure 11 Temperature coefficient

The offset of the X and Y channels at two temperatures has to be known before the coefficient can be calculated with ***Equation 28***.

$$KT_O = \frac{O_2 - O_1}{T_2 - T_1}$$

Equation 28

O_1, O_2 Offset

T_1, T_2 Temperature

The temperature-correct offset can be calculated with the temperature coefficient, the offset at room temperature and the temperature in which the sensor is used.
After the X and Y values are read out, the temperature-corrected offset value must be subtracted:

$$X_1 = X - O_X$$
$$Y_1 = Y - O_Y$$

Equation 29

The next step is to normalize the X and Y values using the mean values determined in the calibration. This results in the offset and amplitude-corrected raw signals of COS and SIN comparable to ***Equation 8***, but including temperature-correct offset.

Revision history

Document version	Date of release	Description of changes
2.0	2018-03-23	New layout, structure changed. TMR based analog angle sensor included.
1.0	2010-12-21	Initial release.

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