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TLE5011

GMR-Based Angular Sensor

Application Note
TLE5011 Calibration

V 1.1

Sensors

Never stop thinking

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TLE5011 GMR-Based Angular Sensor

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1 Giant Magneto-Resistance Parameters

The output signals of the TLE5011 can be factored into a sine (Y) and a cosine (X). These signals can be expressed by **Equation (1)**.

$$X = A_X * COS(\alpha + \varphi_X) + O_X$$
$$Y = A_Y * SIN(\alpha + \varphi_Y) + O_Y \qquad (1)$$

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

The three parameters that affect the angle calculation are the amplitude, the offset, and the phase. **Figure 1** displays the output of X and Y signals. The scale in the figure has been exaggerated to make them easier to see.

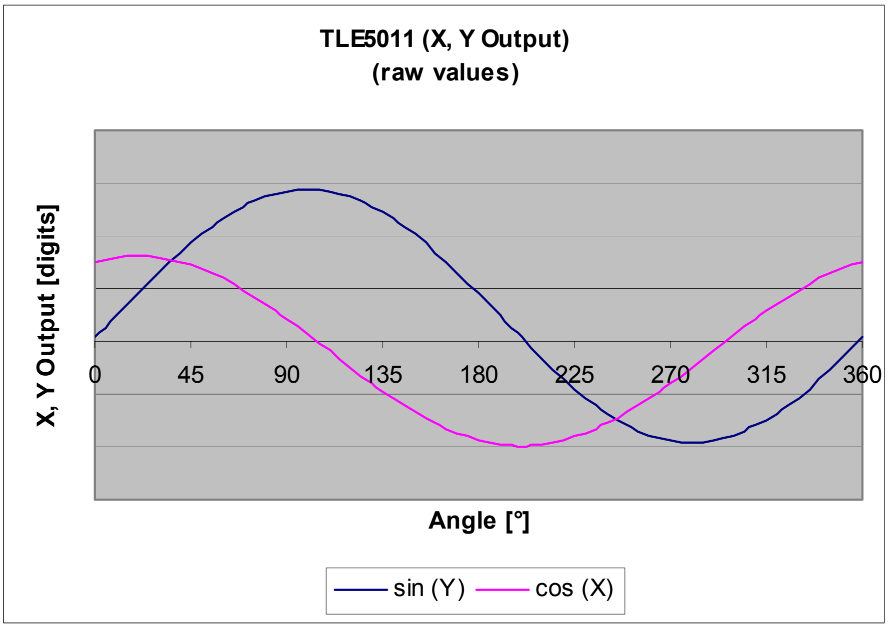

Figure 1 X, Y output signal (raw values)

The direct angle calculation (**Equation (2)**) will result in an elliptical shape (**Figure 2**).

$$\alpha = \arctan\left(\frac{Y}{X}\right) \qquad (2)$$

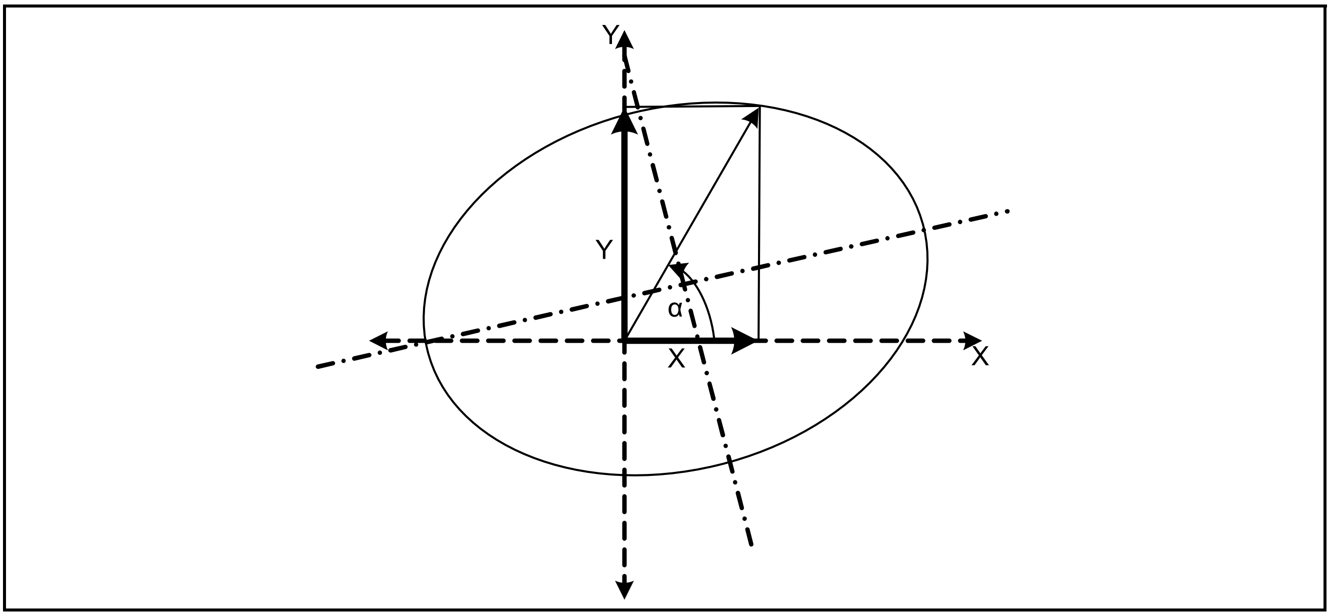

Figure 2 Angle performance without parameter correction

To minimize the angle error, it is important to achieve a circular shape. Therefore some corrections are necessary. First the offset has to be corrected (**Figure 3**).

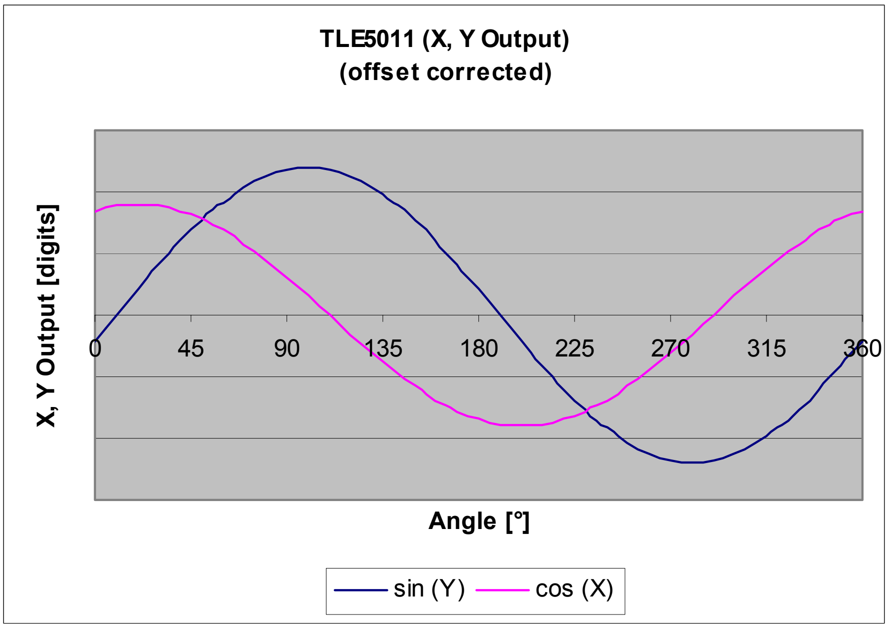

Figure 3 X, Y output signals (offset corrected)

The next step is the amplitude normalization (**Figure 4**), followed by the correction of the non-orthogonality (**Figure 8**).

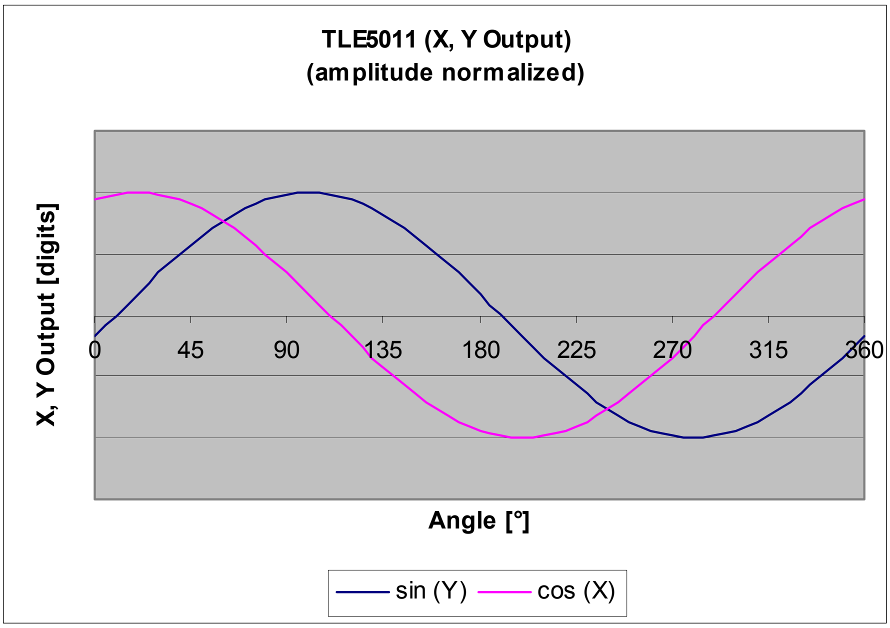

Figure 4 X, Y output signals (amplitude normalized)

After all corrections have been made, the resulting vector of X and Y signal will have a circular shape.

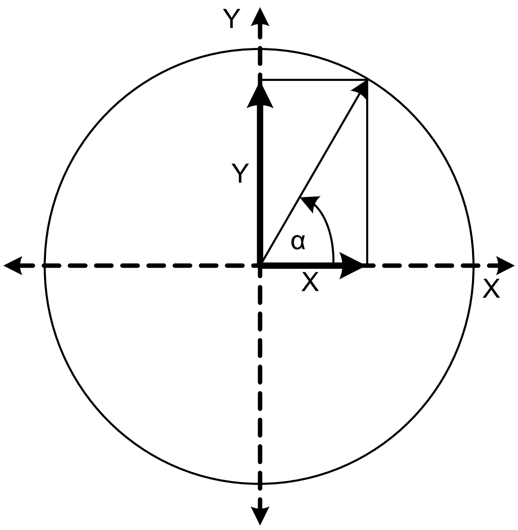

Figure 5 Angle performance after parameter correction

2 Calibration of TLE5011

This chapter explains how to determine the Giant MagnetoResistance (GMR) parameters such as amplitude, offset, and the phase of X- and Y-channels.

The end-of-line calibration can be accomplished using the following sequence (**Figure 6**):

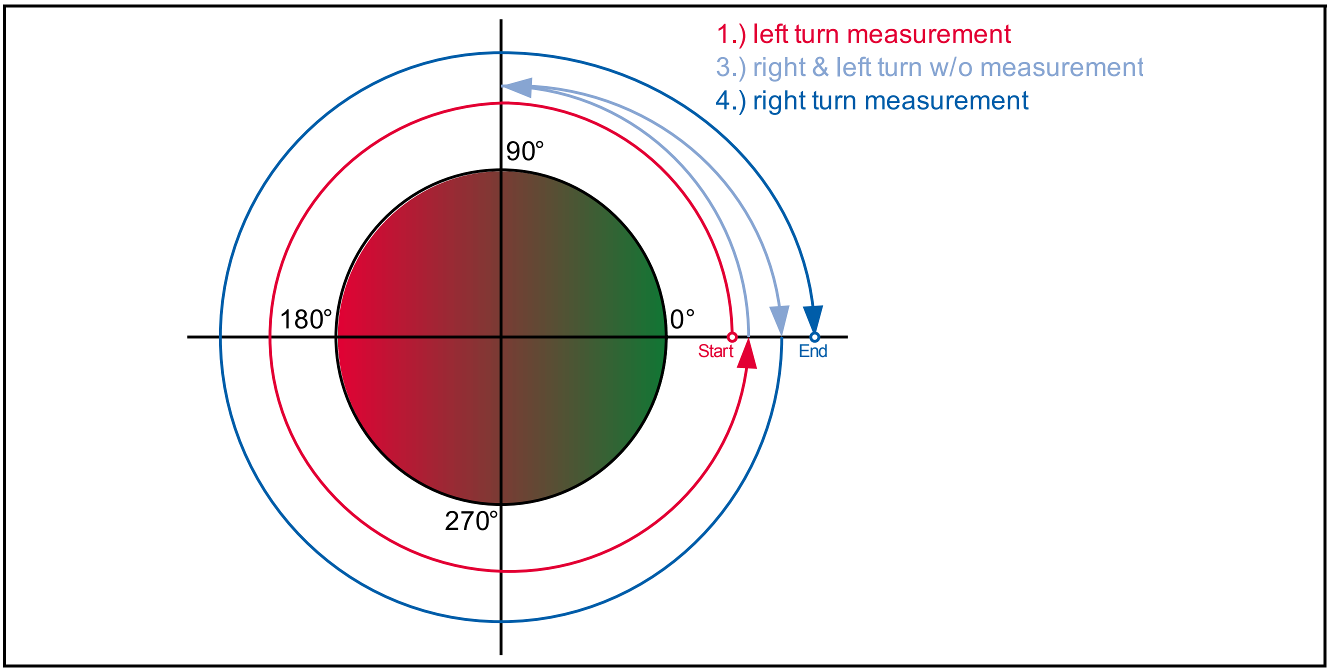

Figure 6 Calibration routine

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

The calibration has to be done at room temperature with a magnet in the specified magnetic field range. The signal amplitude T25 of the temperature measurement path must also be measured afterwards. This is done by setting the TEMP_EN bit at address $0C_H$. The temperature can then be read out via X-path (XL, XH). Store this value in digits; it is not necessary to convert it into °C.

2.1 Extraction of Parameters

There are two possible methods for extracting these parameters. The methods will be discussed in more detail in the next two sections.

2.1.1 Min-Max Method

X_{max}, X_{min}, Y_{max} and Y_{min} have to be extracted out of every full-turn measurement (**Figure 7**).

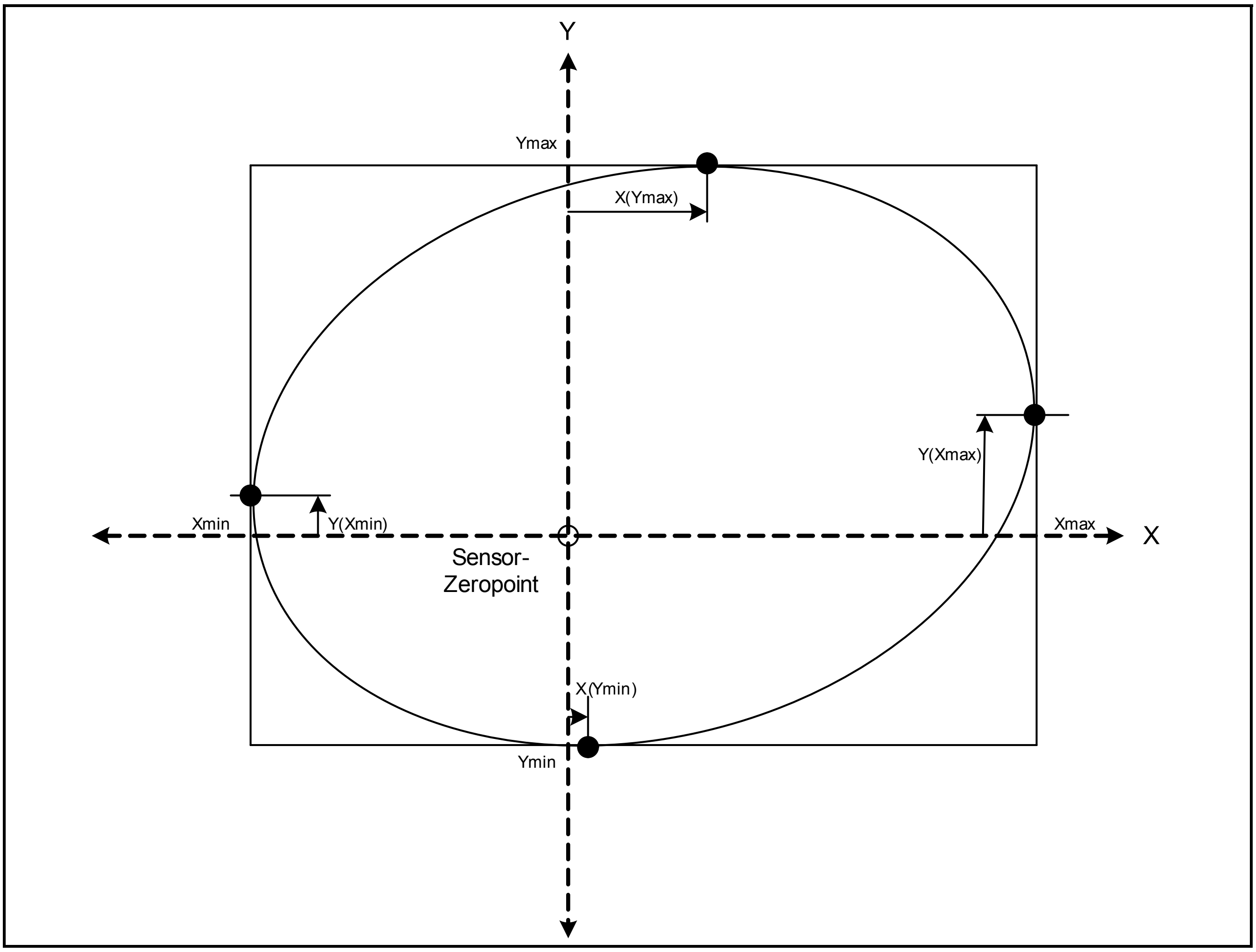

Figure 7 Min-Max method

Afterwards, amplitude (**Equation (3)**, **Equation (4)**) and offset (**Equation (5)**, **Equation (6)**) can be calculated:

$$A_X = \frac{X_{\max} - X_{\min}}{2} \tag{3}$$

$$A_Y = \frac{Y_{\max} - Y_{\min}}{2} \tag{4}$$

$$O_X = \frac{X_{\max} + X_{\min}}{2} \tag{5}$$

$$O_Y = \frac{Y_{\max} + Y_{\min}}{2} \tag{6}$$

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 and Y phases is called the orthogonality error (**Equation (7)**):

$$\varphi = \varphi_X - \varphi_Y \tag{7}$$

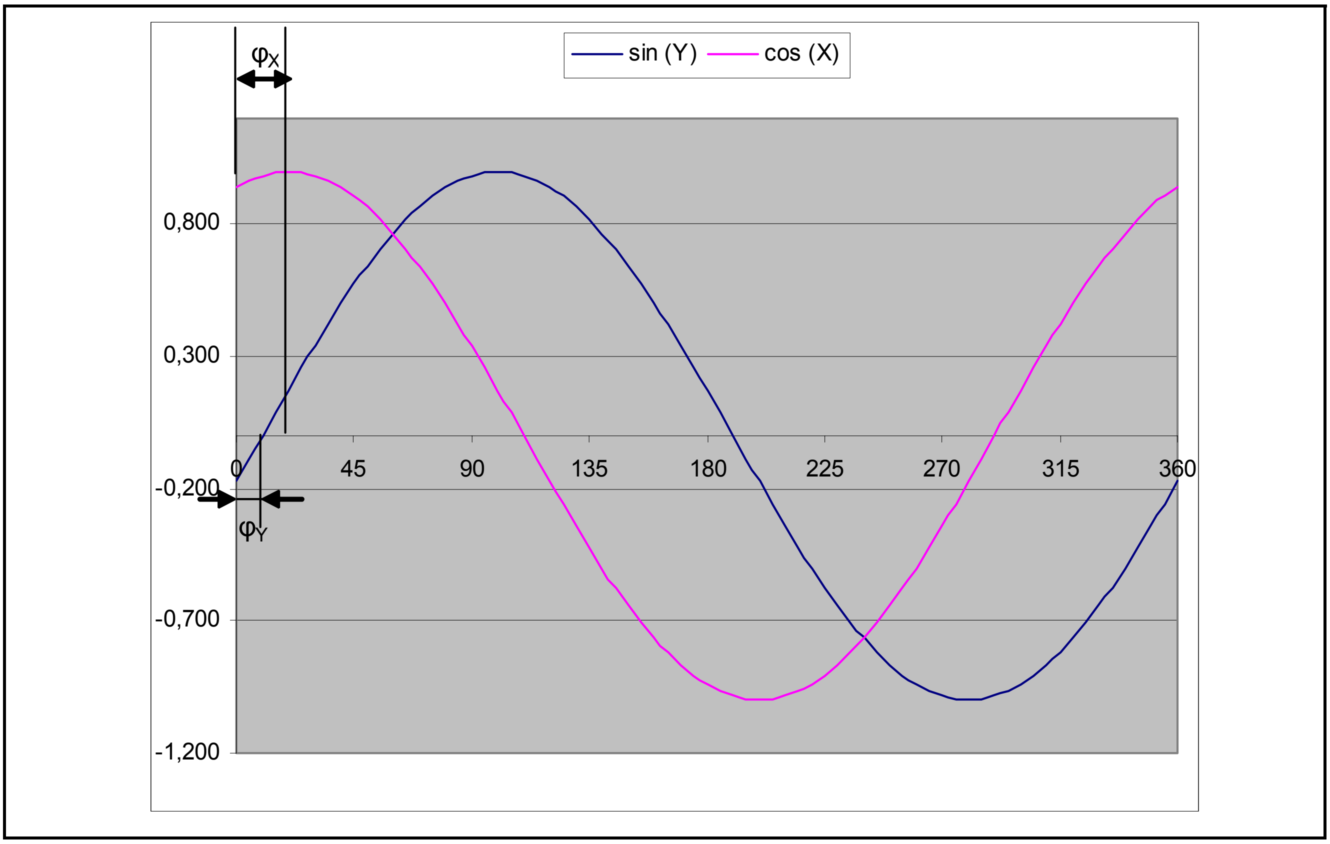

Figure 8 Orthogonality error

There is another more accurate way to determine the orthogonality error. The orthogonality can be calculated out of 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 given by the angle sensor. No reference is necessary. Therefore the final parameters of amplitude and offset (**Chapter 2.2**) should be used.

At an angle output of 45° the corresponding Y(sin) and X(cos) values can be read out. This has been done also at 135° (**Figure 9**).

Next step is to calculate the length of the magnitudes (**Equation (8)**):

$$M_{45} = \sqrt{X_{45}^2 + Y_{45}^2} \qquad M_{135} = \sqrt{X_{135}^2 + Y_{135}^2} \tag{8}$$

M_{45}, M_{135}.. Magnitude at 45° and 135°

X_{45}, X_{135} .. Cosine values at 45° and 135°

Y_{45}, Y_{135} .. Sine values at 45° and 135°

With these magnitudes the orthogonality can be calculated (**Equation (9)**):

$$\varphi = 2 * \arctan(\frac{M_{135} - M_{45}}{M_{135} + M_{45}}) \tag{9}$$

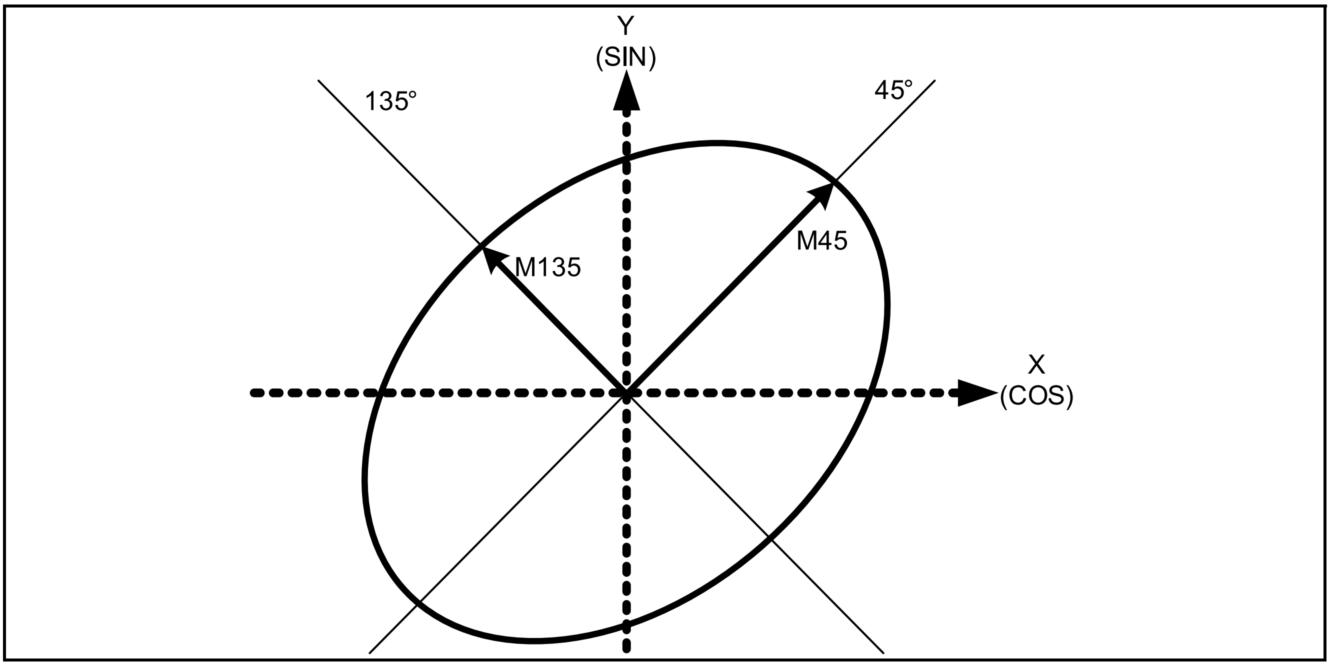

Figure 9 Correction of orthogonality error

2.1.2 Exact Method

This method uses the Discrete Fourier Transform (DFT) to extract the parameters out of 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).

DFT Offset Calculation:

The offset is calculated by the summation of the X- or Y- measurements divided by the number of measurement points (**Equation (10)**):

$$O_x = [X(1) + X(2) + .. + X(n)]/n$$
$$O_Y = [Y(1) + Y(2) + .. + Y(n)]/n \tag{10}$$

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 with **Equation (11)** for the X values and **Equation (12)** for the Y values. β describes the reference angle (e.g. n = 64; measurement every 360° / 64 = 5.625° step).

$$DFT\_X\_r = [X(1)*COS(\beta 1) + X(2)*COS(\beta 2) + .. + X(n)*COS(\beta n)]*2/n$$
$$DFT\_X\_i = [X(1)*SIN(\beta 1) + X(2)*SIN(\beta 2) + .. + X(n)*SIN(\beta n)]*2/n \tag{11}$$

$$DFT\_Y\_r = [Y(1)*COS(\beta 1) + Y(2)*COS(\beta 2) + .. + Y(n)*COS(\beta n)]*2/n$$
$$DFT\_Y\_i = [Y(1)*SIN(\beta 1) + Y(2)*SIN(\beta 2) + .. + Y(n)*SIN(\beta n)]*2/n \tag{12}$$

Now the amplitude and phase can be calculated (**Equation (13)**, **Equation (14)**)

$$A_X = \sqrt{(DFT\_X\_r)^2 + (DFT\_X\_i)^2}$$
$$A_Y = \sqrt{(DFT\_Y\_r)^2 + (DFT\_Y\_i)^2} \tag{13}$$

$$\varphi_X = \arctan\frac{DFT\_X\_i}{DFT\_X\_r}$$
$$\varphi_Y = \frac{\pi}{2} - \arctan\frac{DFT\_Y\_i}{DFT\_Y\_r}$$
$$\varphi = \varphi_X - \varphi_Y \tag{14}$$

2.2 Final Parameters

No matter what calibration method is used, you still have to calculate the symmetrical values of the parameters. This is done using the mean value of the clock-wise (cw) rotation parameters and counterclock-wise (ccw) rotation parameters. This calculation has to be done with X and Y parameters. These parameters have to be used for the signal correction.

$$A_M = \frac{A_{cw} + A_{ccw}}{2}$$
$$O_M = \frac{O_{cw} + O_{ccw}}{2}$$
$$\varphi_M = \frac{\varphi_{cw} + \varphi_{ccw}}{2} \tag{15}$$

$(A,O,\varphi)_M$ .. Mean parameters

$(A,O,\varphi)_{CW}$ .. Parameters of clock-wise rotation

$(A,O,\varphi)_{CCW}$ .. Parameters of counterclock-wise rotation

2.3 Temperature-dependent Behavior

The temperature offset gradients (KT_{OX}, KT_{OY}) for both channels depend on the value at 25°C. These gradients are neccesary for the temperature offset compensation.

$$KT_{Ox} = tco\_d\_x + (tco\_k\_x * O_{X25})$$
$$KT_{OY} = tco\_d\_y + (tco\_k\_y * O_{Y25}) \quad (16)$$

tco_d_x, tco_d_y .. Offset temperature coefficient base (in digits/K)

tco_k_x, tco_k_y .. Offset temperature coefficient gain (in 1/K)

The coefficients (tco_d_x, tco_d_y, tco_k_x, tco_k_y) have to be determined for every sensor separately. This has been done at two different temperatures (e.g. T25 and HT).

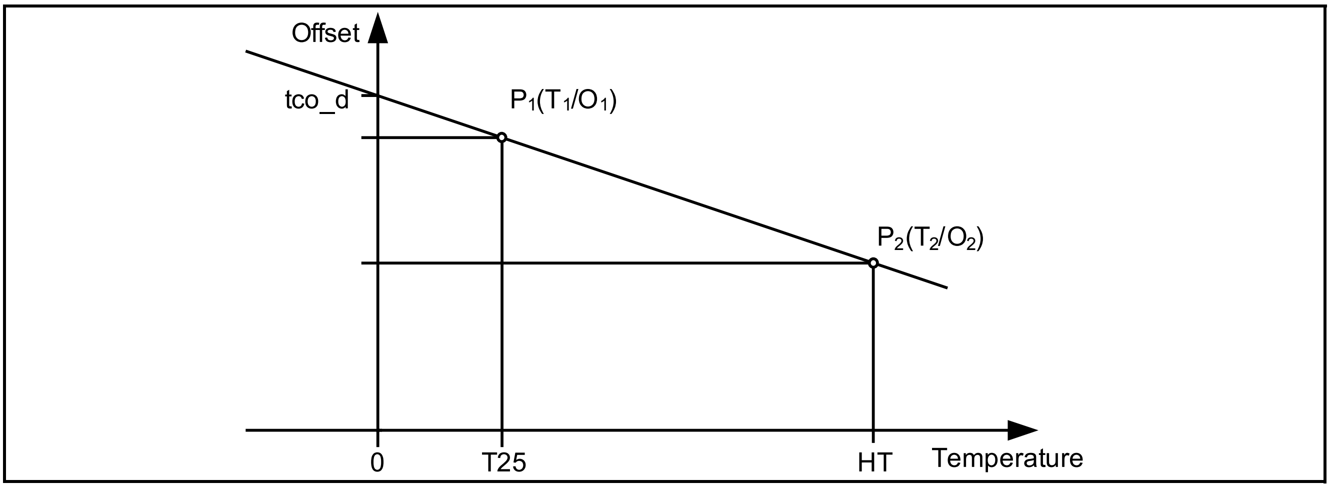

Figure 10 Temperature coefficients

The offset of X and Y channels at two temperatures has to be known before the coefficients can be calculated with **Equation (17)** and **Equation (18)**.

$$tco\_k = \frac{O_2 - O_1}{T_2 - T_1} \quad (17)$$

$$tco\_d = O_1 - tco\_k * T_1 \quad (18)$$

The temperature offset compensation should be used to achieve more accurate angle values over the whole temperature range.

3 Angle Calculation

To get highly accurate angle values, the following angle calculation must be performed. Figure 11 shows the implementation within a microcontroller.

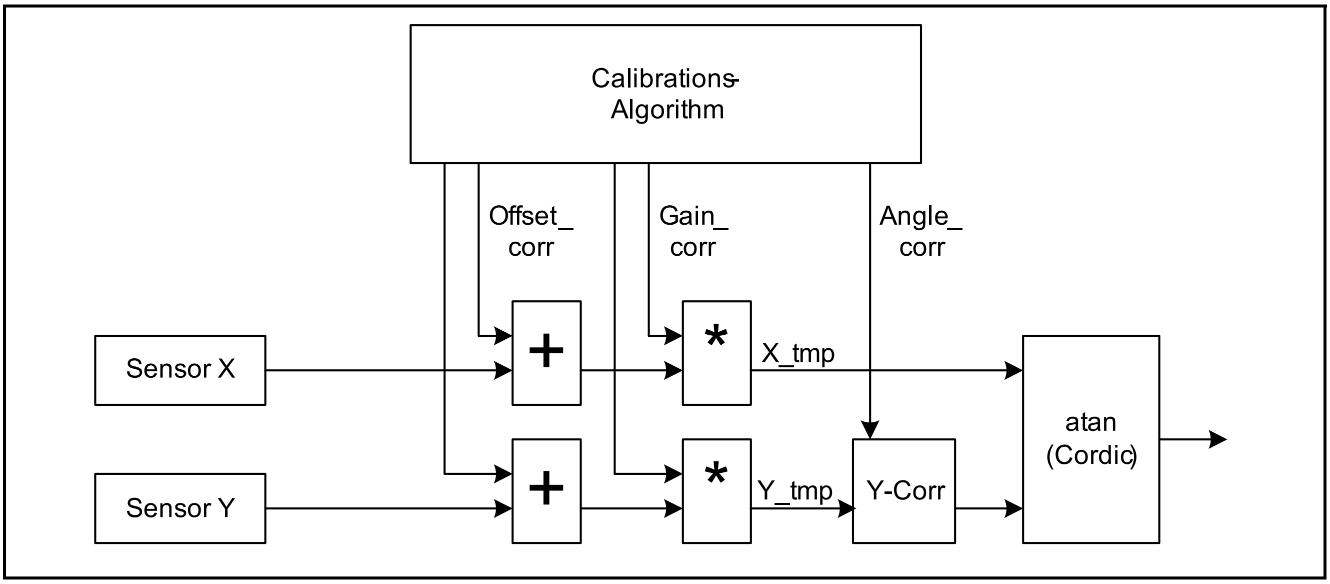

Figure 11 Implementation of angle calculation

Offset Correction (Offset_corr)

To increase the accuracy, the temperature-dependent offset drift can be compensated for. The temperature of the chip has to be read out. The offset values O_X and O_Y can be described by the following equations:

$$O_x = O_{X25} + \frac{KT_{OX}}{S_T} * (T - T_{25})$$
$$O_Y = O_{Y25} + \frac{KT_{OY}}{S_T} * (T - T_{25}) \quad (19)$$

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

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

KT_{OX} .. Gradient of X-offset (in digits/K)

KT_{OY} .. Gradient of Y-offset (in digits/K)

S_T .. Temperature sensor sensitivity (in digits/K)

T .. Temperature (in digits)

T_{25} .. Temperature at room temperature (in digits)

After the X and Y values are read out, the temperature-corrected offset value must be subtracted (Equation (20)):

$$X_1 = X - O_X$$
$$Y_1 = Y - O_Y \quad (20)$$

Amplitude Normalization (Gain_corr)

The next step is to normalize the X and Y values by using the mean values determined in the calibration.

$$X_2 = \frac{X_1}{A_{XM}} \qquad Y_2 = \frac{Y_1}{A_{YM}} \tag{21}$$

Non-Orthogonality Correction (Angle_corr)

The influence of the non-orthogonality can be compensated for by using **Equation (22)**, in which only the Y channel must be corrected.

$$Y_3 = \frac{Y_2 - X_2 * \sin(-\varphi)}{\cos(-\varphi)} \tag{22}$$

Resulting Angle

After correction of all errors, the resulting angle can be calculated using the arctan function[1].

$$\alpha = \arctan\left(\frac{Y_3}{X_2}\right) - \varphi_X \tag{23}$$

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

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