SIDE-SHAFT POSITIONING OF MAGNETIC ANGLE SENSORS

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INTRODUCTION

If a magnetic angle sensor is used in a side-shaft application with a diametral magnet (Figure 1), the sensor angle output is typically non-linear (Figure 2). There are two ways to address this issue:

- Using angle sensors with integrated linearization features
- Choosing a linear sensor position (here referred to as "diagonal sensor position")

Both possibilities offer advantages and disadvantages, described in the next two sections.

This application note provides an empiric formula to calculate the best possible side-shaft sensor position(s) to obtain a linear sensor output. The formula can be used independently from the magnet material.

Classic Side-Shaft Position With On-Chip Linearization

Figure 1 shows a typical side-shaft configuration. The sensor is placed next to a diametral ring magnet in the same plane. To achieve linear output behavior, the sensor signal can be linearized by a lookup table or harmonic compensation. This type of linearization can be performed in:

- A microcontroller / microprocessor [1]
- A modern angle sensor with integrated linearization [2][3]

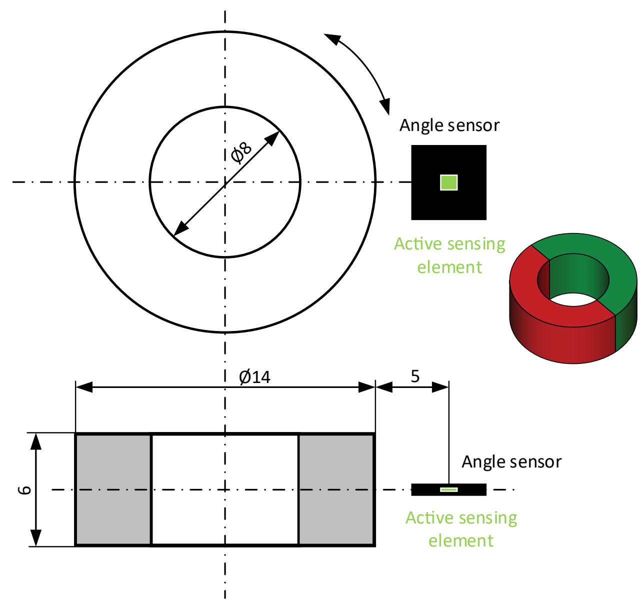

Figure 1: Side-shaft measurement, classic positioning

After linearization, the sensor angle is close to the desired output (see Figure 2).

Although after linearization the sensor output equals the real angle in theory, intrinsic sensor angle errors have different effects at different positions.

[1] See application note Microcontroller-Based Linearization of Angular Sensor ICs.

[2] See application note Linearization Parameter Calculation for Allegro AAS33001 and AAS33051 Angle Sensor ICs.

[3] See application note Advanced On-Chip Linearization in the A1335 Angle Sensor IC.

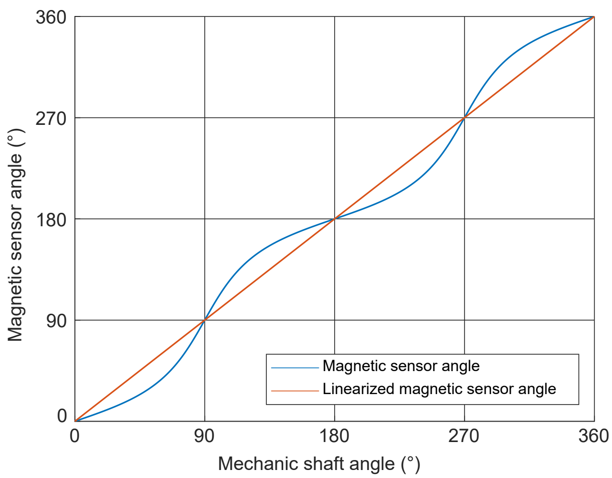

Figure 2: Side-shaft sensor (encoder) signal

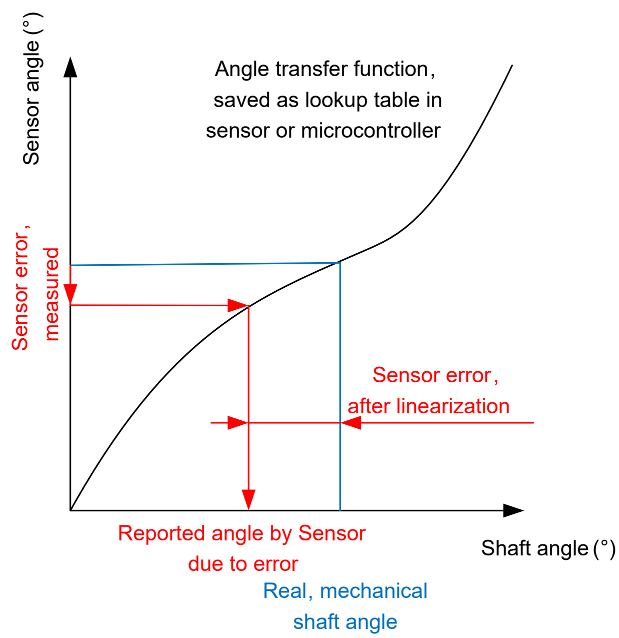

Figure 3: Sensor error amplification

Figure 3 shows the reason for this behavior. The transfer function, saved in the sensor or microcontroller, takes in the sensor angle (y-axis) and transfers it to the real mechanical angle (x-axis), shown in blue. This deviation can have significant effects on the reported shaft angle by the linearized sensor, shown in red.

Assuming a sensor with an accuracy of ±1°, there will be different accuracies at different angles:

- Mechanic rotation from 45° to 135° (rotation +90°)
  - □ Sensor raw signal change 132.4°
  - □ Ratio between shaft and sensor angle

$$\frac{\Delta\alpha_{shaft}}{\Delta\alpha_{sensor}} = \frac{90°}{132.4°} = 68\%$$

  - □ A sensor with an intrinsic angle error of ±1°, will see an angle error of ±0.68° in this area (on average)
- Mechanic rotation from 135° to 225° (rotation +90°)
  - □ Sensor raw signal change 47.6°
  - □ Ratio between shaft and sensor angle

$$\frac{\Delta\alpha_{shaft}}{\Delta\alpha_{sensor}} = \frac{90°}{47.6°} = 189\%$$

  - □ A sensor with an intrinsic angle error of ±1°, will see an angle error of ±1.89° in this area (on average)

This is caused by the magnetic field direction changing frequently in certain positions and less in other positions. The angle error is therefore not consistently spread in this case. It is important to note that this effect is a physical effect of the transfer function, which is dependent on the geometry of the magnet. This is not always a disadvantage. In applications where only a small angle needs to be measured, areas with a lot of signal change can be used with higher accuracy. In the example above, this would be the case for the shaft angles from 45° to 135° or from 225° to 315°.

The example shown above is typical for side-shaft configurations. If a steady sensor accuracy over 360° is required and increased angle errors cannot be accepted, this is disadvantageous.

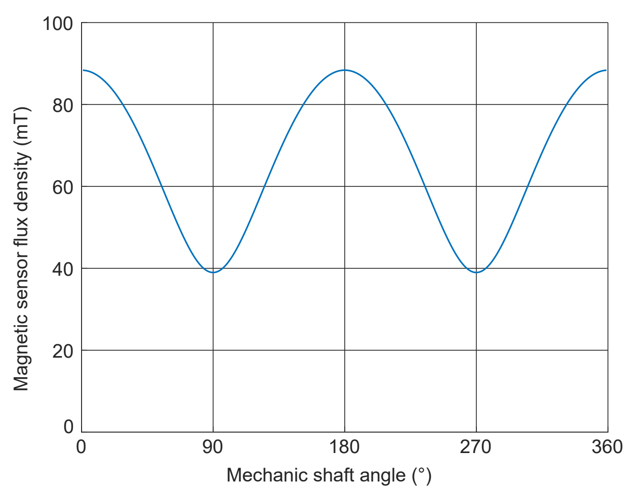

Figure 4: Side-shaft sensor signal strength (in sensor plane)

Due to the shape of diametral magnet flux lines, the sensor sees varying flux densities (Figure 4). As less flux density typically causes more noise, noise is dependent on the mechanical shaft angle for this configuration.

Diagonal Side-Shaft Positioning

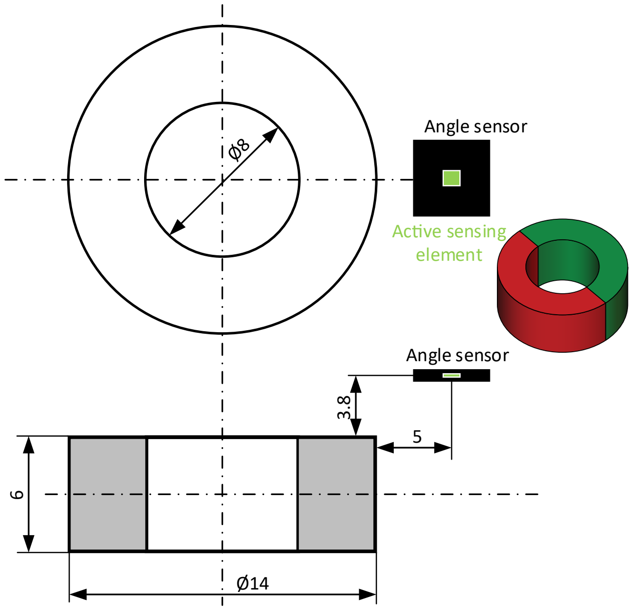

Figure 5: Side-shaft measurement, "diagonal" positioning

In cases when linearization is not possible (e.g., no microcontroller is available) and the sensor does not provide on-chip linearization, the sensor output can still give a linear output by choosing the correct sensor position. Also, if the effect of inconsistent angle accuracy described in the previous section cannot be accepted, changing to a "diagonal" side-shaft position offers a good solution. By changing to a "diagonal" side-shaft position, as shown in Figure 5, the magnetic angle measured by the sensor becomes linear over the mechanical shaft angle without the need for linearization.

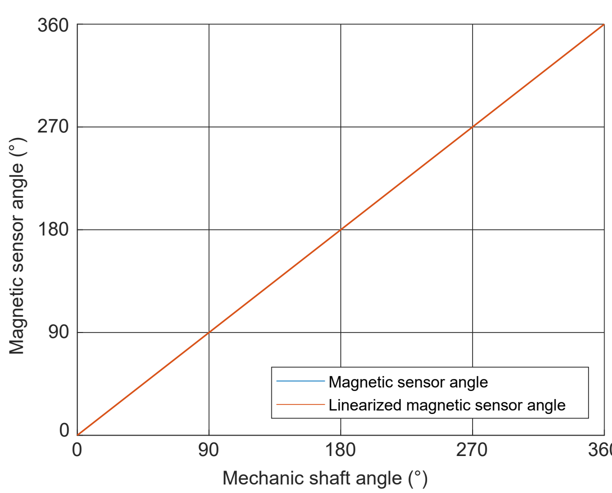

Figure 6: Side-shaft sensor (encoder) signal, "diagonal" positioning

The sensor output angle over mechanical rotation in Figure 6 shows that the sensor angle equals the mechanical shaft angle.

Figure 7 shows the flux density at the sensor for the "diagonal" positioning. Compared to the classic side-shaft position, at the same radial air gap distance (Figure 4), flux density is reduced in the diagonal positioning. At first, this seems like a disadvantage, as smaller flux densities typically increase noise. But side-shaft positions typically allow for smaller air gaps, as the sensor package can be placed to the side of the diametral magnet, which can compensate the loss of flux density.

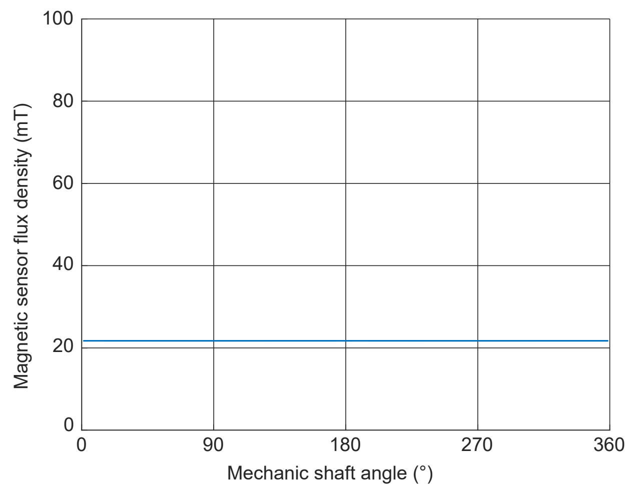

Figure 7: Side-shaft sensor signal strength, "diagonal" positioning

Example For "Diagonal" Side-Shaft Positioning

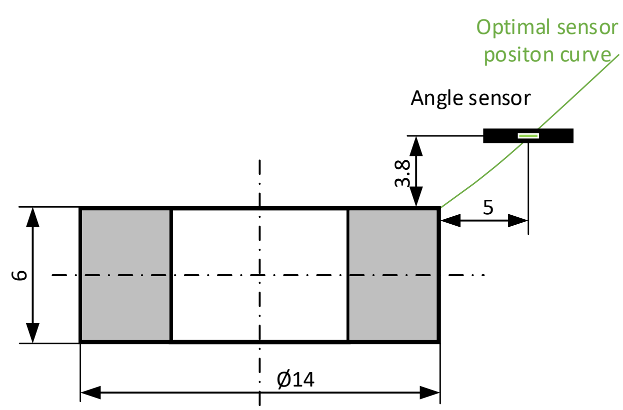

Figure 8: Line of ideal position

For the example given in this application note, Figure 8 shows the line for optimal sensor position in green.

The line is a two-dimensional representation of a three-dimensional funnel. As the diametral magnet is mirrored at the horizontal plane, the sensor can also be placed at the same mirrored coordinates beneath the magnet. The shape of the line/funnel depends on the magnet geometry and is not always straight.

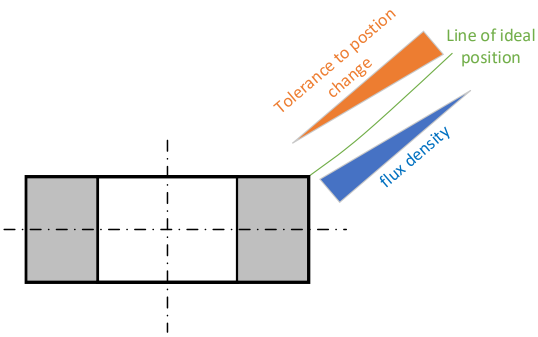

Figure 9: Positioning trade-off

Figure 9 demonstrates the tradeoff between placing the sensor close to or far from the magnet.

- Sensor close to magnet rim
  - □ High flux density, small noise
  - □ Small positioning tolerance
- Sensor far from magnet
  - □ Low flux density, high noise
  - □ Bigger positioning tolerance

The positioning tolerance is zero millimeters at the edge of the diametral magnet and increases with the air gap.

A general positioning recommendation cannot be given and is best evaluated in each application. In general, it is good to start evaluation as close to the magnet as mechanically possible.

Calculation For Best Sensor Coordinates

For any given magnet geometry, it is possible to calculate the ideal height Z above the top of the magnet plane using an empirical formula.

Table 1: Geometry limits for formula

Symbol	Name	Min.	Max.	Units
D	Outer diameter	1	40	mm
d	Inner diameter / outer diameter	0	0.95	–
T	Thickness	1	10	mm
AG	Radial air gap [4]	1	D/4	mm
Z	Axial air gap			mm

Table 1 with geometry boundaries represents limits of the simulated geometries. The limits are not strict, and the formula will work beyond its limits, but with reduced accuracy. It is not recommended to go far above or below the given minimum and maximum values.

For applications with geometries not covered by this formula, contact your Allegro representative.

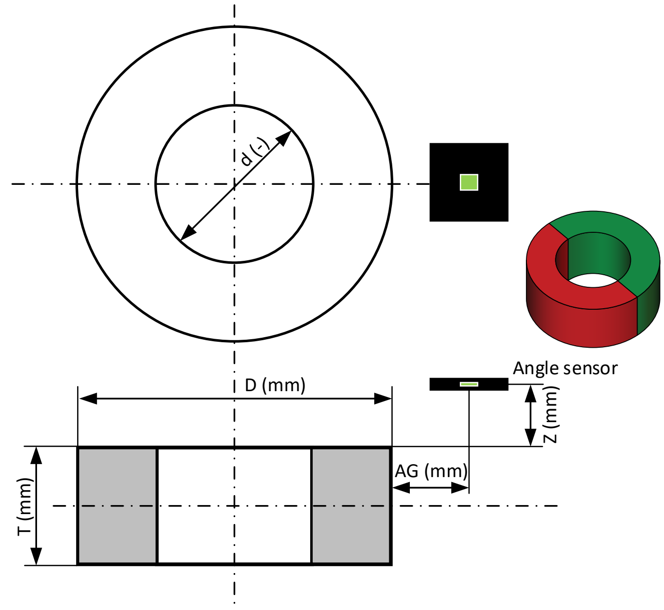

Figure 10: Variables for calculating the right position height Z

The formula is given in the Appendix. The naming convention is given in Table 1 and is explained in Figure 10.

Conclusion

This document describes two different methods to magnetically measure linear angle in side-shaft positions:

- Using angle sensors with digital linearization
- Choosing a sensor position that provides a linear output

For side-shaft applications where a digital linearization is not possible or where areas of reduced accuracy cannot be accepted, choosing the right sensor position is a good way to achieve a linear output. In practice, the following points must be considered:

- Accuracy limits in the calculation
  - □ ±1° accuracy for 95% of all cases
  - □ ±2° accuracy for 98% of all cases
- Mechanical tolerances
- Sensor tolerances
- Inhomogeneous diametral magnet

The formula offers a starting point to optimize designs to the ideal sensor position. Optimization can be done by adjusting the sensor position or by additionally using digital linearization.

[4] For geometries smaller than 15 mm, a maximum radial air gap of D/2 can be used.

Appendix

The formula gives the ideal height (Z in mm) as a function of the air gap (AG in mm), the outer diameter (D in mm), the inner diameter (d in as a fraction of D) and thickness (T in mm). It is intended for digital use; the reader of this document can copy the formula into a program of choice, e.g., MATLAB.

```
Z = 1.475e-08*D^5 + 6.2995e-07*D^4*d + 8.415e-08*D^4*T - 8.2536e-08*D^4*AG - 2.8052e-06*D^4 -
2.5098e-05*D^3*d^2 + 2.0298e-06*D^3*d*T - 2.2788e-06*D^3*d*AG - 3.3526e-05*D^3*d + 8.2389e-08*D^3*T^2
- 2.603e-07*D^3*T*AG - 1.0022e-05*D^3*T - 8.2485e-07*D^3*AG^2 + 2.2317e-05*D^3*AG + 0.00016744*D^3 -
0.00067958*D^2*d^3 - 4.0225e-05*D^2*d^2*T + 0.00018137*D^2*d^2*AG + 0.0029254*D^2*d^2 - 9.7592e-06*D^2*d*T^2
- 4.3338e-06*D^2*d*T*AG - 7.0462e-05*D^2*d*T - 1.4062e-05*D^2*d*AG^2 + 0.00017321*D^2*d*AG +
0.00014415*D^2*d - 1.4218e-07*D^2*T^3 + 1.9872e-06*D^2*T^2*AG - 2.6121e-06*D^2*T^2 - 1.2287e-06*D^2*T*AG^2
- 2.1638e-06*D^2*T*AG + 0.00045219*D^2*T + 9.1939e-07*D^2*AG^3 + 7.427e-05*D^2*AG^2 - 0.0015226*D^2*AG
- 0.0047136*D^2 + 0.075131*D*d^4 - 0.00030893*D*d^3*T + 0.0051079*D*d^3*AG - 0.11828*D*d^3 +
0.00033793*D*d^2*T^2 + 7.0365e-05*D*d^2*T*AG + 0.00083405*D*d^2*T + 0.0019046*D*d^2*AG^2 - 0.046516*D*d^2*AG
- 0.0082367*D*d^2 + 8.5949e-05*D*d*T^3 + 3.3957e-05*D*d*T^2*AG - 0.0014542*D*d*T^2 - 0.00019356*D*d*T*AG^2
+ 0.0012818*D*d*T*AG + 0.0093056*D*d*T - 0.00010861*D*d*AG^3 + 0.0039608*D*d*AG^2 - 0.019494*D*d*AG
- 0.0090736*D*d + 6.7087e-07*D*T^4 + 7.8691e-06*D*T^3*AG - 6.9403e-05*D*T^3 + 3.3512e-06*D*T^2*AG^2 -
0.00031529*D*T^2*AG + 0.001393*D*T^2 - 3.9679e-05*D*T*AG^3 + 0.00067521*D*T*AG^2 - 0.00039614*D*T*AG
- 0.01718*D*T - 8.7562e-06*D*AG^4 + 0.00061485*D*AG^3 - 0.011995*D*AG^2 + 0.094589*D*AG + 0.084167*D -
0.88488*d^5 - 0.057256*d^4*T - 0.29746*d^4*AG + 1.7563*d^4 - 0.0017137*d^3*T^2 + 0.0083233*d^3*T*AG +
0.15398*d^3*T - 0.022296*d^3*AG^2 + 0.49962*d^3*AG - 1.389*d^3 - 0.0010097*d^2*T^3 + 0.0026464*d^2*T^2*AG
+ 0.0020548*d^2*T^2 - 0.0075253*d^2*T*AG^2 + 0.0033974*d^2*T*AG - 0.021098*d^2*T - 0.0054597*d^2*AG^3 +
0.17082*d^2*AG^2 - 0.6936*d^2*AG + 0.62738*d^2 - 0.00019302*d*T^4 - 0.00039992*d*T^3*AG + 0.0045425*d*T^3
+ 0.00011817*d*T^2*AG^2 + 0.0053978*d*T^2*AG - 0.028709*d*T^2 + 0.0010255*d*T*AG^3 - 0.0090305*d*T*AG^2
- 0.015088*d*T*AG + 0.039153*d*T + 0.00028055*d*AG^4 - 0.012152*d*AG^3 + 0.05504*d*AG^2 + 0.11511*d*AG -
0.11618*d - 8.3703e-06*T^5 - 4.3112e-05*T^4*AG + 0.00050687*T^4 + 2.4733e-05*T^3*AG^2 + 0.0010416*T^3*AG
- 0.0093419*T^3 + 0.00018053*T^2*AG^3 - 0.0033842*T^2*AG^2 + 0.0051993*T^2*AG + 0.071207*T^2 +
5.4241e-05*T*AG^4 - 0.0038543*T*AG^3 + 0.055155*T*AG^2 - 0.24382*T*AG - 0.18093*T - 2.1967e-06*AG^5 -
0.00020358*AG^4 + 0.012094*AG^3 - 0.12805*AG^2 + 1.0686*AG - 0.11225
```

Revision History

Number	Date	Description	Responsibility
–	July 10, 2020	Initial release	T. Ostermann
1	November 30, 2022	Updated hyperlinks (page 1)	R. Couture

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