Application Note

AN000573

Adaptive Noise Filter

AS5047U, AS5147U, AS5247U

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Content Guide

1 Introduction

In all products of the magnetic position sensor product family AS5x47U, an adaptive noise filter is implemented to reduce random measurement errors.

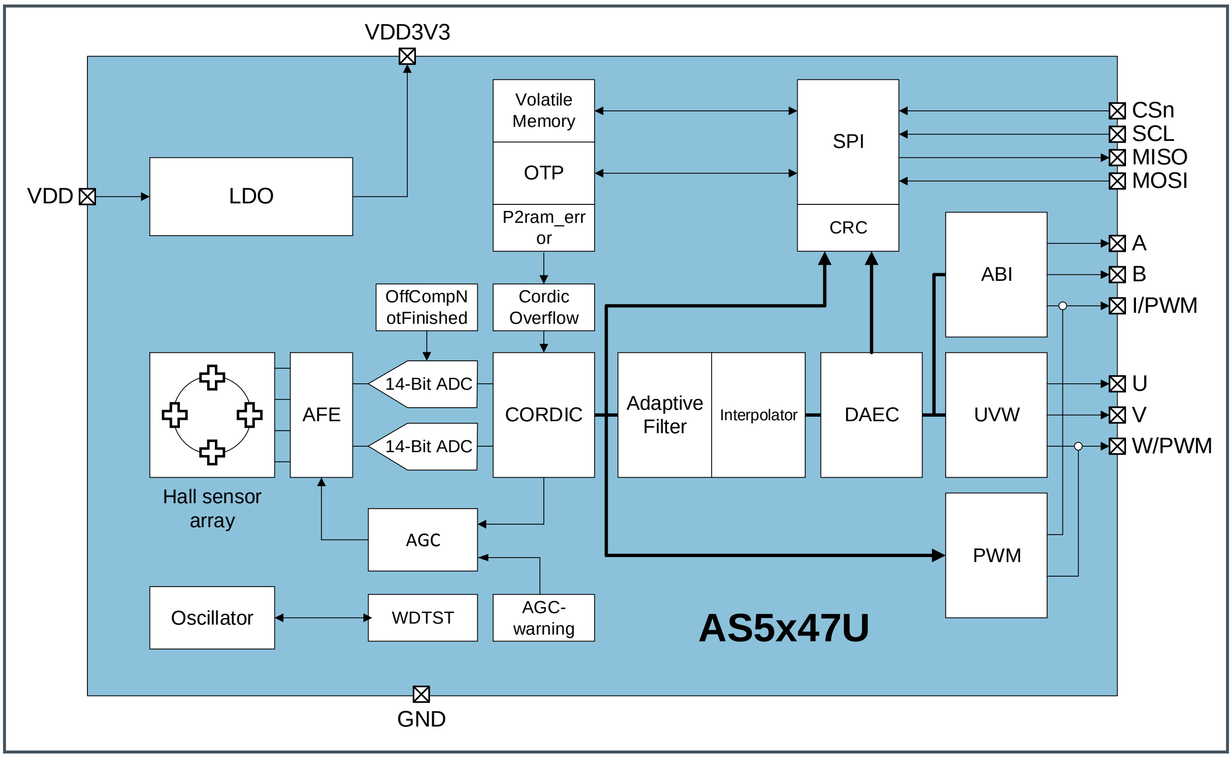
Based on the implemented filter, it is possible to reduce the random measurement error, respectively the output noise, by a factor of six. Due to the adaptive approach, the capability to deal with very dynamic systems is not affected. Rotation speed up to 28000 rpm in combination with massive acceleration rates are handled without any constraints. It is guaranteed, that no positions or measurement points will get lost due to filtering.

The application note gives a deep insight into the filter design and implementation. Many details about timing and function are explained. To optimize system performance it is possible to adapt filter parameters, although the default settings will fit to most of all possible applications.

2 Filter Details

The adaptive filter bock is implemented in the digital part of the sensor. Basis for all filters and further interpolation is the 14-bit core angle value, which is generated out of the CORDIC.

Figure 1:
Block Diagram AS5x47U



2.1 Adaptive Filter Block Description

Figure 2 shows a detailed block diagram of the filter block itself. It consists of following blocks:

1. Rotation speed calculation
   - Angle samples provided with 10 kHz sample rate (100 µs)
   - Calculation of rotation speed based on actual and previous RAW angle sample
   - Rotation speed vector is updated with 10 kHz sample rate (100 µs)
   - Rotation speed information available on SPI (register 0x3FFC)
2. Angular acceleration calculation
   - Rotation speed information provided with 10 kHz sample rate (100 µs)
   - Calculation of angular acceleration based on actual and previous speed vector

3. K-Value selection

- Angular acceleration provided with 10 kHz sample rate (100 µs)
- K-Value, respectively band with limit selection based on actual angular acceleration
- 7 steps from 48 kHz to 3095 kHz available

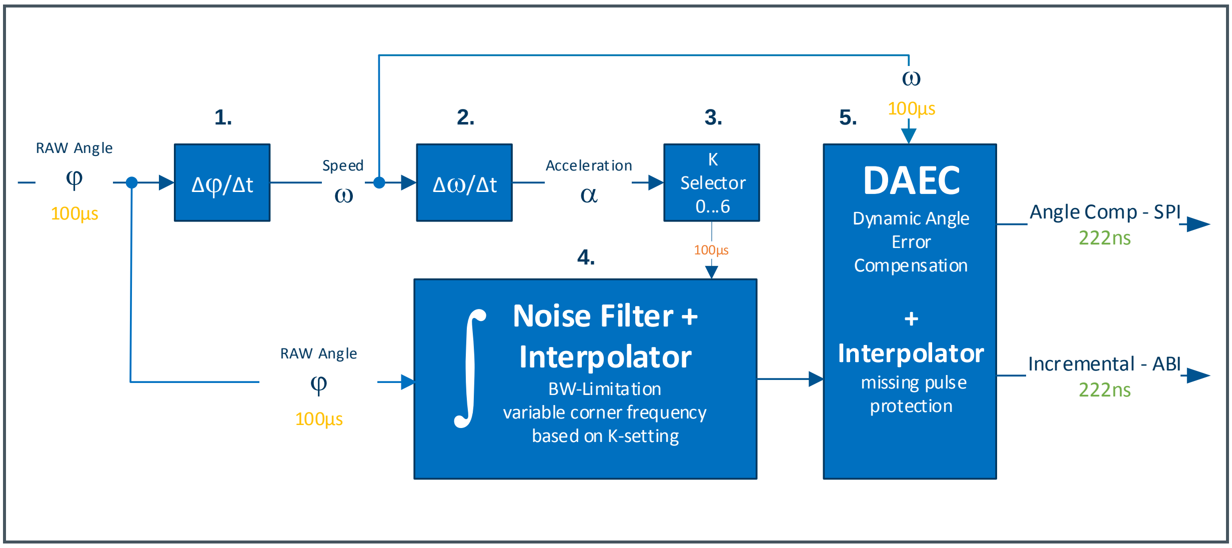
4. Noise Filter + Interpolator

- RAW Ange data provided with 10 kHz sample rate (100 µs)
- K-Value provided with 10 kHz sample rate (100 µs)
- Noise filter acts as a low pass filter with variable BW (band width)
- BW selection by provided K-Value
- Filter generate filtered and interpolated data with 4.5 MHz sample rate (222 ns)

5. DAEC (Dynamic Angle Error Compensation)

- Filtered angle samples are provided with 4.5 MHz sample rate (222 ns)
- Rotation speed vector is provided with 10 kHz sample rate (100 µs)
- DAEC compensates for all delays which occur in sensor signal path based on provided angle speed
- Remaining propagation delay of 1.9 µs max. at constant rotation speed
- Additional interpolator guarantees that no pulses will be lost at the incremental outputs (ABI, UVW)

Figure 2:
DFS Block Diagram



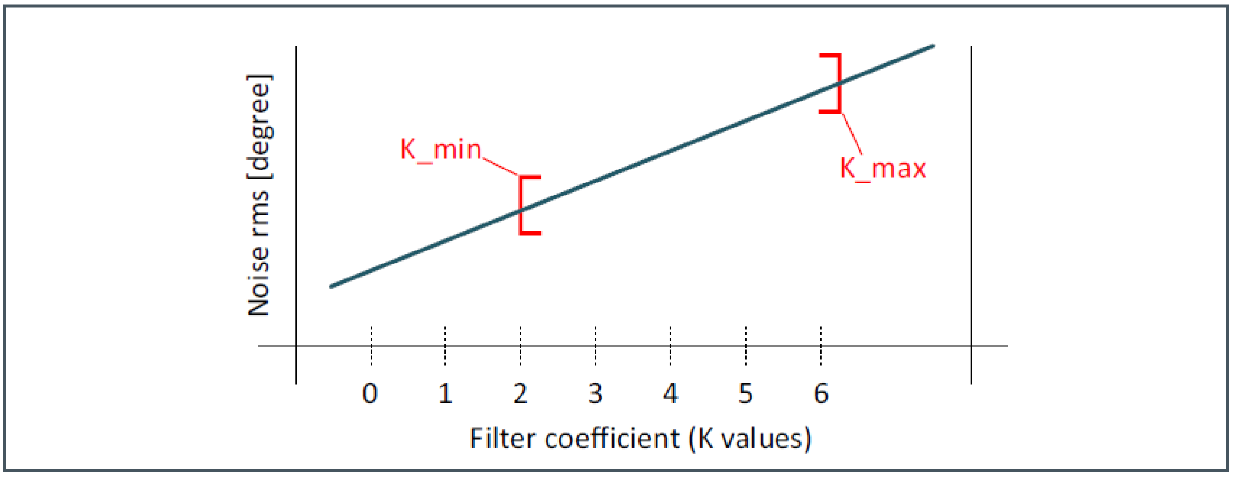
2.2 DFS Corner Frequency Setting

The dynamic filter selects the ideal corner frequency automatically based on the actual angular acceleration. The K-Value divides the corner frequencies into 7 steps. At a fixed angle (no rotation) or at constant rotation speed (no acceleration) the filter chooses a low corner frequency to reduce the noise as much as possible. During acceleration or deceleration, the corner frequency increases immediately. With this approach, no angle information will be lost and the sensor can react with sufficient dynamic. The BW (bandwidth) selection reacts on every speed measurement sample and has a death time of 100 µs maximum.

In addition, the user can define the maximum and minimum K-Value within the 7 available steps. For very dynamic system with high acceleration rates, it could make sense to block the lowest K-Values. This needs to be evaluated and optimized by the user itself.

Within default configuration, the K-Settings K-0 and K-1 are disabled. This configuration fits to most of the systems in the field of motor control applications. For low speed applications with lots of inertia and low noise requirements, it could make sense to enable the lowest K-Value within OTP-Setting.

Figure 3:
K-Values Default Range



It is also possible to fix one K-Value to one defined point, as well as switching off the filter completely.

2.3 Filter Related SPI-Register

In SPI register SETTINGS1, limits for K_min and K_max are defined.

In SPI register FILTERSTATUS, it is possible to read the actual selected K-Value chosen based on the actual acceleration.

Figure 4:
SETTINGS1 (0x0018)

Name	Read/Write/Program	Bit Position	Description
K_max	R/W/P	2:0	Defines K_max of the adaptive filter range
K_min	R/W/P	5:3	Defines K_min of the adaptive filter range

Figure 5:
FILTERSTATUS (0x00F6)

Name	Read/Write/Program	Bit Position	Description
K_adpt	R	2:0	Actual status of K-Setting chosen by the filter

The table in Figure 6 describes the possible settings for K_max and K_min. As default K_min = 2 and K_max = 6. This setting will fit to most of applications related to motor control applications.

For low speed applications with lots of inertia and low acceleration, K_min could be set to 1 or 0. The result is lower output noise. Although, in dynamic systems additional angle errors and side effects could be introduced if the K_min setting is too low. See also section Filter vs. INL.

Modification of K_max is only necessary if the user wants to fix the K-Value to a specific setting. If the user sets K_min = 0 and K_max = 0, the filter will fix the bandwidth to the lowest value. In this case, no adaptive regulation is possible.

Figure 6:
K-Value Configuration

K_min [LSB] K_max [LSB]	Minimum K Value	Maximum K Value
000	2 (default)	6 (default)
001	3	5
010	4	4
011	5	3
100	6	2

K_min [LSB] K_max [LSB]	Minimum K Value	Maximum K Value
101	0	1
110	1	0
111	1	0

Figure 7 shows the worst-case noise figures in relation with the actual chosen K-Value. Numbers are valid over lifetime and temperature. Typical noise figures are way smaller and shown in Figure 9.

Figure 7:
Corner Frequency vs. Noise

K Value Actual chosen K value by the filter	fcorner Filter corner frequency [Hz]	ONFdyn RMS-Noise during rotation [deg]	ONFstat RMS-Noise when stand still [deg]
0	48	0.019	0.011
1	97	0.028	0.017
2	194	0.036	0.032
3	387	0.048	0.044
4	773	0.062	0.059
5	1548	0.077	0.077
6	3095	0.086	0.084

3 Filter Related Measurements and Tests

Following section treats different measurement results with static and dynamic systems, to show the prospects of the filter and the K-Value selection.

3.1 Static Noise Measurements

Magnet fixed at a certain angle position over the sensor. Several samples were taken to calculate the noise figures in P2P (peak to peak) and RMS (standard deviation, STD).

Figure 8 illustrates histogram plots based on 10000 angle value readings. Histogram on the left side shows the distribution of angle values with K-Setting = 6 (highest bandwidth).P2P-Noise (Peak to peak noise) of 0.3° represents the worst situation regarding noise and is equal to the performance without filter.

Histogram on the right side shows the same measurement, but with K-Value fixed to 0 (lowest bandwidth). Peak to peak noise is reduced by a factor of 6 down to 0.044°.

Figure 8:
Histogram Plots of Multi Angle Readings at Fixed Position

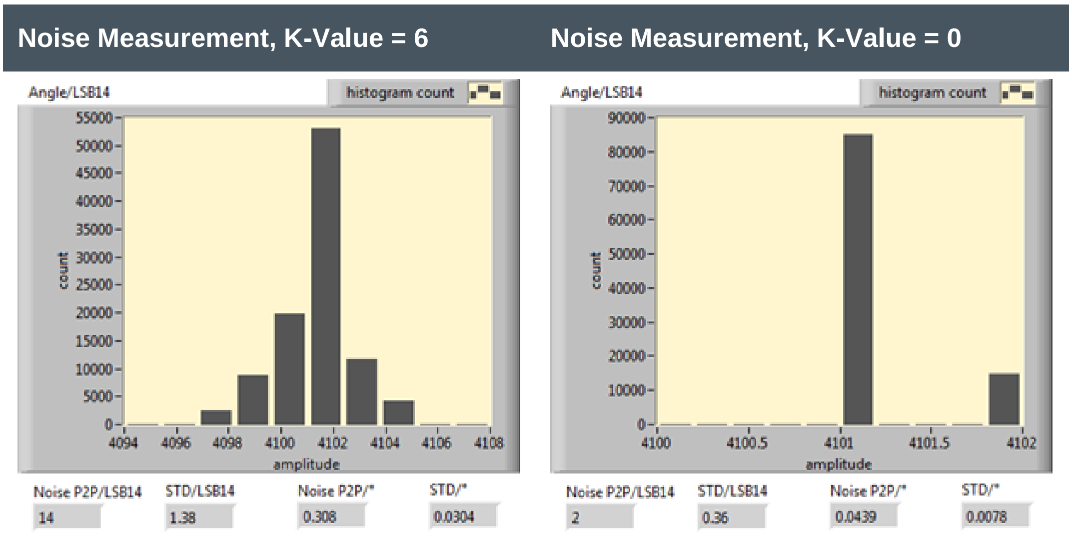
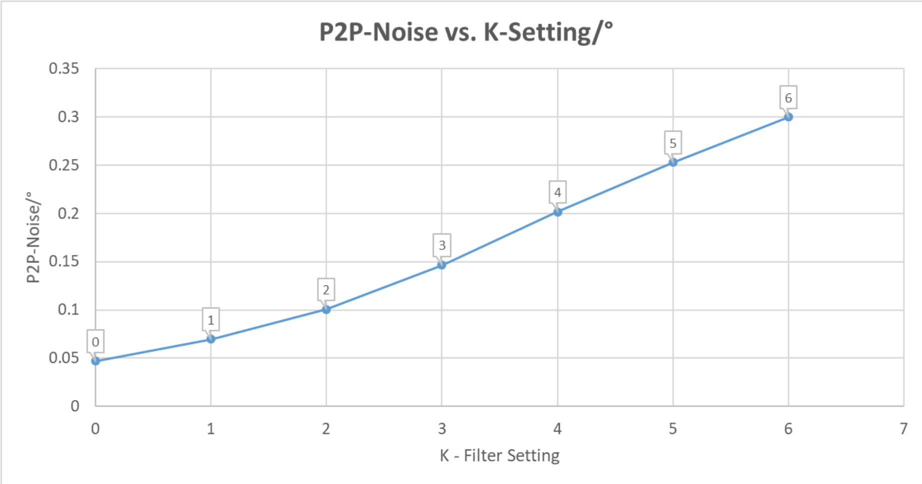


Figure 9 depicts the P2P-Noise for every possible K-Value. Noise level is linear increasing related to the defined bandwidth. Typical measured noise figures at room temperature are much lower than specified worst-case number in Figure 7.

Figure 9:
Measured Peak to Peak Noise vs. K-Value Settings



3.2 Dynamic Comparison between Rotation Speed and K-Value

The dynamic filter system chooses automatically the correct bandwidth based on the actual acceleration. Figure 10 shows based on a measurement example the switching behavior and automatic K-Value selection. The yellow curve represents the actual rotation speed; the blue curve represents the selected K-Value.

A high-speed BLDC motor is accelerating and deaccelerating the magnet from 0 – 30 krpm within 50 ms. Therefore the example represents a very dynamic system and confirms the capability of the dynamic bandwidth selection.

Figure 10:
Exemplary Acceleration Profile with Read Back of K-Value

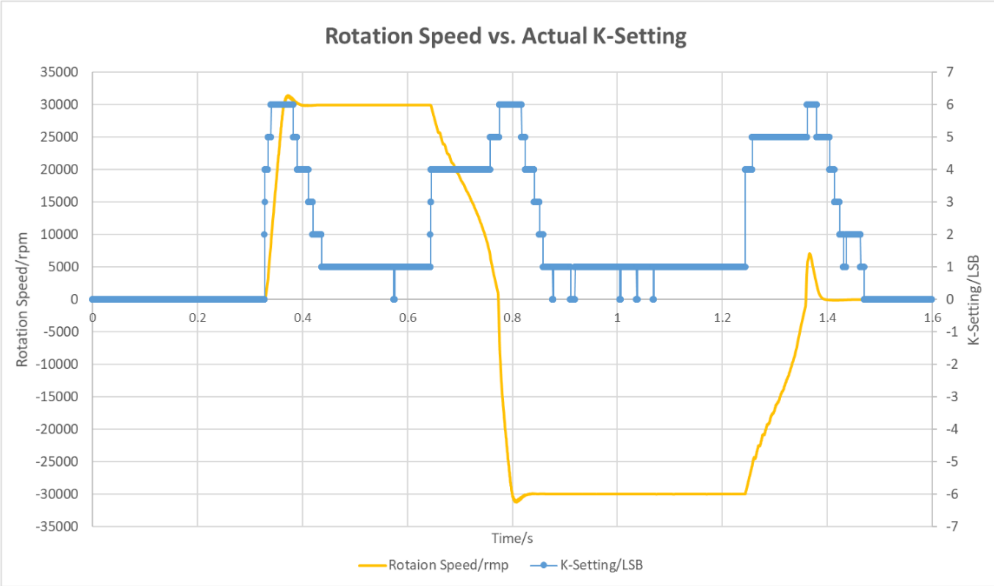
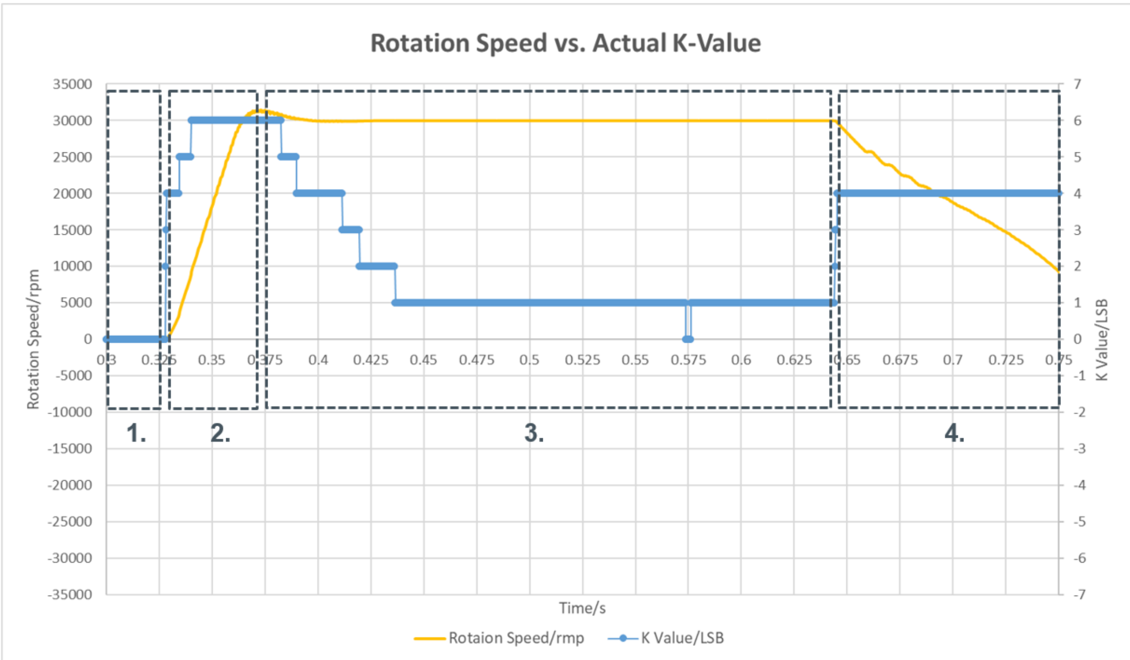


Figure 11 shows the first section of the acceleration profile in detail. The 0.45 seconds are divided into 4 segments of acceleration, constant speed and deceleration.

Figure 11 :
Exemplary Acceleration Profile - Zoom in Section



The table in Figure 12 points out again the relation between filter setting and angular acceleration. Even very high acceleration rates like 70 krad/s² are handled without any problem.

Figure 12:
Angular Acceleration vs. K-Setting

Section	Rotation Speed [rpm]	Angle Acceleration [rad/s²]	K-Setting
1	0	0	0
2	0 – 30000	70000	0 – 6
3	30000	0	6 – 1
4	30000 – 10000	-20100	1 – 4

The test shows clearly the behavior and the character of the adaptive filter system. Fast reaction and proper bandwidth selection is given up to highest rotation speeds.

3.3 Filter vs. INL

An essential parameter of an angle sensor is of course the absolute accuracy respectively the linearity of the angle measurement. It represents the deviation from the measured to the real angle position. In case of the AS5x47U this parameter is defined in the datasheet as INL (Integral nonlinearity), with a limit of ± 0.8° in combination with an ideal placed magnet. INL is a systematic measurement error and independent form random measurement errors like noise.

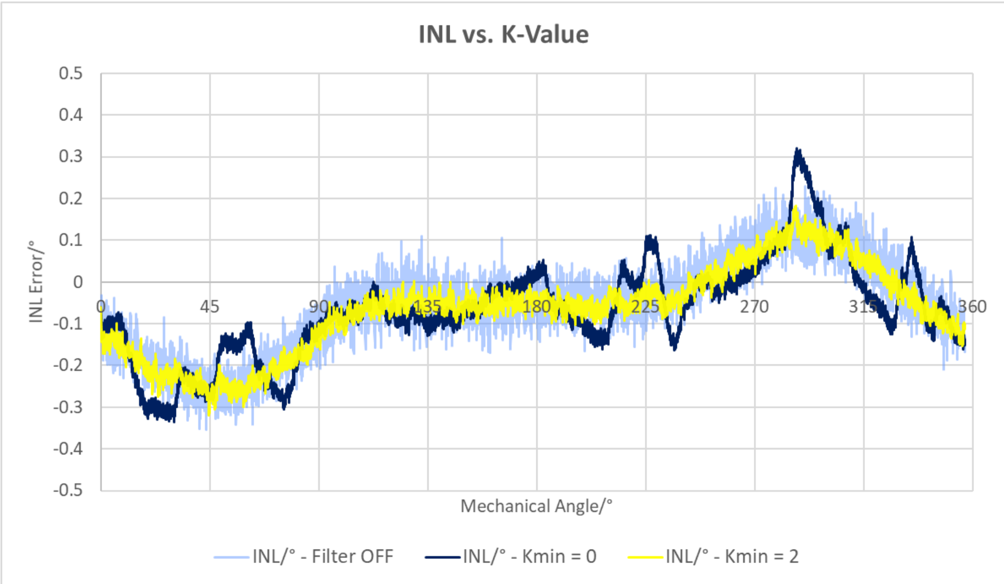
Every filter is influencing the transfer function of a system. This is also the case for the AS5x47U sensor. Therefore, also the systematic measurement error has to be considered during definition of BW-limits.

Based on simulation and evaluation during engineering phase of the sensor, minor influences on the INL were identified. Especially with the lowest K-Settings (setting 0 and 1), variations of the systematic measurement error could occur. Nevertheless, the linearity error stays bellow the spec limit of the INL parameter.

Figure 13 shows an exemplary measurement of linearity error over one mechanical rotation from 0 – 360°. Magnet rotated with constant speed of 50 rpm. Measurement was done for different filter settings. Ideally, the INL error curve would be a straight line at zero. In reality, a deviation around 0° of ± 0.3° is given and way typical for a well aligned system.

The three different colored lines represent different filter settings. The light blue line shows raw data without filtering (highest noise). The yellow line shows the same measurement with enabled filter and default K-Setting setting (K_min = 2). Noise is reduced and the systematic error is following the same curve as without filter. The dark blue line shows the error curve with K_min value of 0 (48 Hz corner frequency). Lowest BW, lowest noise but small degradation of the systematic part of the measurement is given.

Figure 13:
INL Over One Mechanical Rotation and Different K-Value Settings



This behavior needs to be considered by the user, especially if the application requires an external linearization of the sensor data. For applications without linearization, the behavior is uncritical. With the default configuration of the filter (K_min = 2, K_max = 6), no effect of the INL shape is expected.

The whole filter configuration is part of a system optimization process and needs to be evaluated by the user itself. Again, usually the default configuration fits quite well and no modifications are required.

4 Summary / Results

The DFS of the AS5x47U product family adds significant value to the device. Reduction of random measurement error (noise) by a factor of 6 is given.

Filter chooses BW-Limit automatically based on the actual acceleration. Therefore, the sensor is able to run low speed and very dynamic high speed applications with the same settings.

The default configuration of the filter block is well evaluated and chosen. In addition, it is possible to select the BW limits within the configuration registers of the AS5x47U by the user itself. In special cases, it could make sense to use the lowest BW frequencies or even fix the BW to a constant value. This is part of a system optimization process and needs to be evaluated by the user itself.

5 Revision Information

Changes from previous version to current revision v1-00	Page
Initial version	

- Page and figure numbers for the previous version may differ from page and figure numbers in the current revision.
- Correction of typographical errors is not explicitly mentioned.

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