Definition of the encoder signal criteria

Summary

Explanations of the definitions of the encoder attributes for FAULHABER encoders.

Applies To

FAULHABER incremental and absolute encoders.

Description

1. General description

Output signals

Specification of the type and number of an encoder's output signals.
With incremental encoders (square wave signals), one distinguishes between encoders with two channels (e.g., IE2, IEH2) and those with three channels (e.g., IE3, IEH3, IER3).
Besides the two channels A and B for the quadrature signals, encoders with three channels are characterized by an additional channel for one index pulse per revolution.

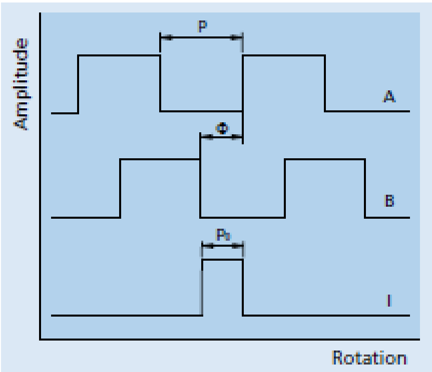

Figure 1: Typical output signals of an incremental encoder with two quadrature channels and an index pulse (index signal)

Absolute encoders (AES) deliver the absolute angle information via an expanded synchronous serial interface (SSI). The AES interface is described in detail in application note AN130.

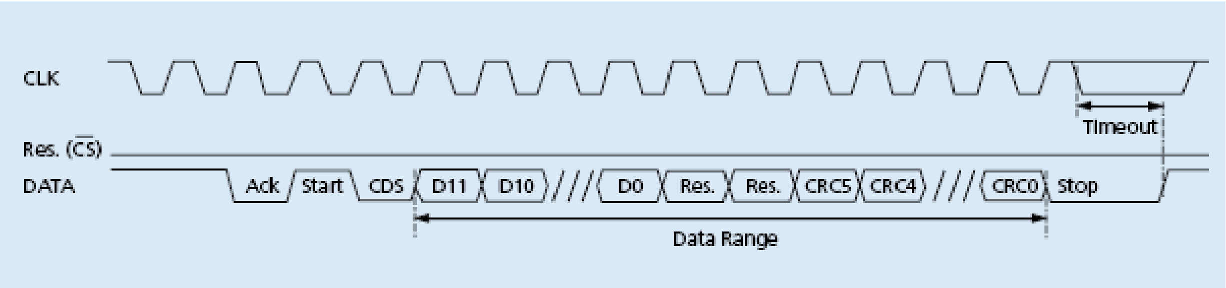

Figure 2: Interface signal (SSI) of an AES encoder

Signal period

Is the entire period of a quadrature signal on channel A or channel B in °e. One signal period is typically 360°e.

Lines per revolution (N)

Specifies how many pulses are generated at the incremental encoder's outputs per channel and per revolution. For the quadrature signal, two edges are available per channel within a signal period, i.e., a total of four edges. If the encoder has e.g. 1024 lines per revolution, this yields a possible resolution of 4096 edges per revolution.

Steps per revolution

The parameter "steps per revolution" specifies the number of position values per motor revolution. The value is generally used with absolute encoders and corresponds to the resolution or number of edges for incremental encoders (see *Lines per revolution (N)*).

Pulse width P

Width of an output pulse (in °e) of the encoder channels A and B. Normally, it is 180°e (Figure 1, pulse width P)

Signal phase shift ϕ

The phase shift between output signals A and B is referred to as signal phase shift and is ideally 90°e (see Figure 1 and *Phase error*).

Measuring step

Distance of two adjacent edges (in °e) between the two channels A and B. There are four measuring steps (S) per signal period. Normally, a measuring step is 90°e. This attribute corresponds largely to the *Signal phase shift* ϕ as which is used for most FAULHABER encoders.

Index pulse widthP_0

Specifies the width of the index pulse in °e. The width is ideally 90°e (Figure 1).

Index position

Normally, the position of the index signal is synchronised with the edges of the signals A and B. Figure 3, left, shows the standard position of the index signal relative to signals A and B for the encoder types IEH3-4096 and IER3-10000 (with the motor rotating clockwise when looking at the motor shaft). Figure 3, right, shows the same for the encoder IE3-1024.

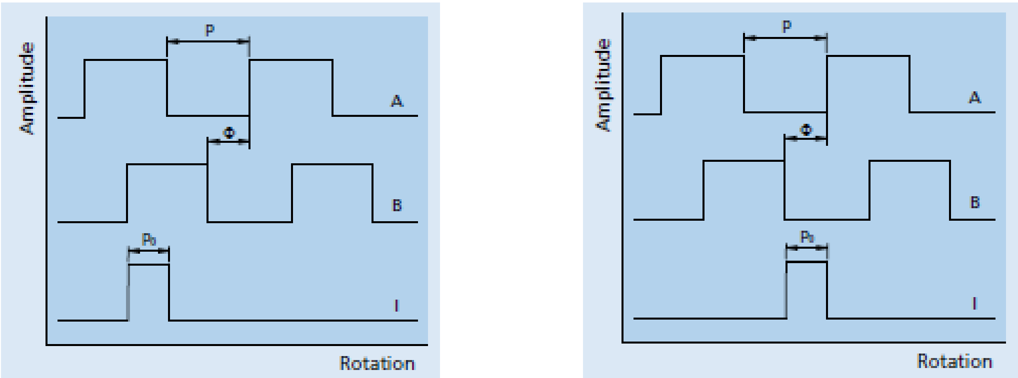

Figure 3: Index position with the motor rotating clockwise

2. Definition of the encoder attributes (acc. To FAULHABER standard)

In the following, all attributes, which are specified in the data sheets or recorded as attributes during the final test, are explained and defined. All attributes do not need to be defined in every data sheet. It is also not mandatory that every attribute in the data sheet be an attribute that is tested. This document only provides a general overview of all attributes used at FAULHABER.
Moreover, note that, at FAULHABER, the time (between two successive edges) is used by default as the reference value for determining the parameters. This results in a **constant speed** for the measurement. The measurement uncertainty that is attributable to possible speed fluctuations within a motor revolution is negligible for most parameters. This does not apply to the *Repeatability*. It may be necessary to compensate for the speed fluctuations here.
In addition to a time measurement, it is also possible to use a highly precise and high-resolution reference encoder as measuring device.

Phase error

The phase error is the error that can occur between two successive edges at channels A and B.

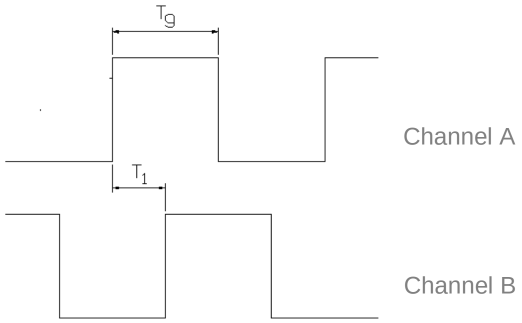

Figure 4: Phase shift between signals A and B

In order to determine the phase error for a given edge, one needs a reference angle. We therefore define the time between the respective previous and following edge of the adjacent channel as 180°e. Ideally, the edge to be determined would be exactly in the middle between the two edges of the other channel and would thus be 90°e. We define the deviation from 90° as the relative phase error (Figure 4).

ϕ_{Error}	$[°e]$	*Phase error of a given edge*
T_1	$[s]$	*Time from the previous edge of the other channel to the determinant edge*
T_G	$[s]$	*Time from the previous edge to the following edge (pulse width P)*

$$\boldsymbol{\Phi_{Error}} = \left|\mathbf{180°}\boldsymbol{e} * \frac{\boldsymbol{T_1}}{\boldsymbol{T_G}} - \mathbf{90°}\boldsymbol{e}\right|$$ **Formula 1**

Index pulse width errorΔP_0

The pulse width error of the index signal is defined analogously to the phase error. The given pulse width (or pause width) at channel A represents the reference value here (Figure 3, left).

ΔP_0	$[°e]$	*Pulse width error of the index signal*
P_0	$[°e]$	*Index pulse width*
P	$[°e]$	*Pulse/pause width at channel A*

$$\boldsymbol{\Delta P_0} = \left|\mathbf{90°}\boldsymbol{e} - \frac{\boldsymbol{P_0}}{\boldsymbol{P}} * \mathbf{180°}\boldsymbol{e}\right|$$ **Formula 2**

Duty cycle

The duty cycle is calculated for each period using the ratio of switch-on time (high) to switch-off time (low) (see formula 3). From all of the calculated values, the worst value is output.

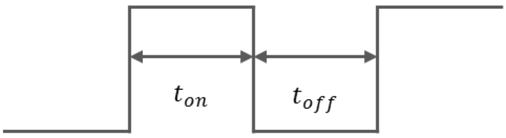

Figure 5: Determination of the duty cycle

d	s	*Duty cycle*
t_{on}	s	*Switch-on time / pulse duration of a channel*
t_{off}	s	*Switch-off time / impulse pause of a channel*

$$\boldsymbol{d = \frac{t_{on}}{t_{off}}}$$

Formula 3

Frequency ripple

The frequency is determined mathematically for each period of an encoder channel. Using the following formula 4, the frequency ripple is then determined as the ratio of the highest to lowest frequency.

w	s	*Frequency ripple*
f_{max}	s	*Max. frequency*
f_{min}	s	*Min. frequency*

$$\boldsymbol{w = \frac{f_{max}}{f_{min}}}$$

Formula 4

Angular hysteresis

With incremental encoders, it is possible to set an angular hysteresis which, in the event of a change of direction of rotation, prevents the channels from switching multiple times. In Figure 6, an example of the edge sequence is sketched for a hysteresis of 0.7°.

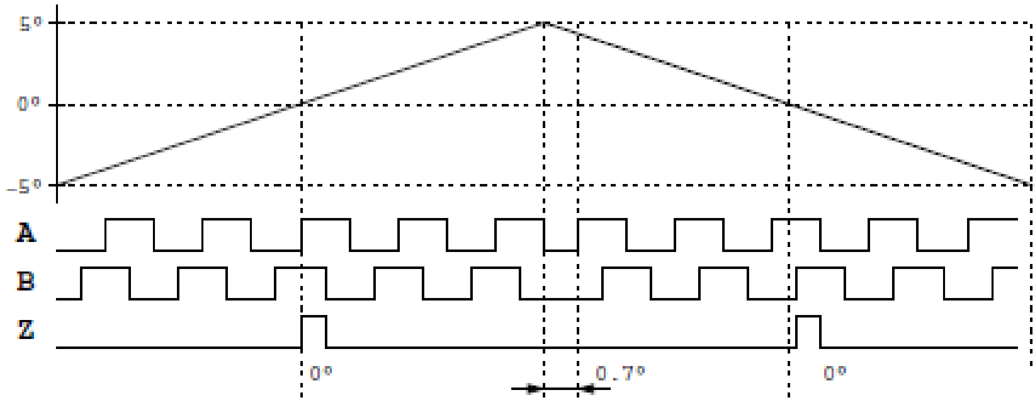

Figure 6: Edge sequence in the event of a change of direction of rotation **(source: data sheet iC-MH16, iC-Haus, 2015)**

The angular hysteresis is apparent here only if the direction is reversed. If the switching point is approached from the same direction, the corresponding edge is ideally always generated at the same position.
Listed in Table 1 are typical settings of the hysteresis for various encoders:

Encoders	**Angular hysteresis [°m]**
IE2-64…512	0.04
IE2-1024	0.09
IEH2-16…2048	0.175
IEH2-4096	0.35
IEH3	0.35
IE3	0.17
IER3/IERS3	0.05
IEP3-4096	0.04
IEX3-4096 (L)	0.04

Table 1: Typical values of the angular hysteresis

For a large portion of the listed encoders (IE2, IEH2, IEH3, IE3, IEP3, IEX3), this parameter can be configured variably to a certain extent and, as a result, can be increased or decreased in a targeted manner depending on requirements.

Note: If a gearhead is also installed at the motor, the electrical angular hysteresis of the encoder may be superimposed by the mechanical hysteresis of the gearhead (gear backlash).

Minimum edge spacing

The smallest possible (temporal) spacing between two successive edges (edge spacing) of the quadrature signal represents the characteristic variable for determining the speed required for processing the encoder signals. For a reliable evaluation of the quadrature signal, a motor controller is needed that is able to detect this minimum edge spacing.
It is calculated from the ideal edge spacing at a given maximum output frequency and the permissible phase error.

T_{min}	$[s]$	*Minimum spacing between two successive edges*
ϕ_{Error}	$[°e]$	*Phase error of a given edge*
f	s^{-1}	*Max. output frequency of the encoder*

$$\boldsymbol{T_{min} = \frac{1}{f*4} * \left(1 - \frac{\Phi_{Error}}{90°el}\right)}$$ **Formula 5**

For an IE2-1024 encoder with a frequency range of up to $f = 300\ kHz$ and a maximum phase error of 45°e, this then results in a minimum edge spacing of $T_{min} = 41.67\mu s$.

For some encoder systems, the edge spacing is an adjustable parameter that can be configured during chip programming (IE3, IEHX). It also determines the converter speed of the interpolator. Typical values for this can be found in Table 2:

Encoders	Minimum edge spacing $[ns]$
IEH2/IEH3	250
IE3	500
IER3	125
IEP3	125
IEX3 (L)	125

Table 2: Typical values of minimum edge spacing of various encoders

Position accuracy

Ideally, the output edges of an encoder with 1024 lines per channel and revolution (i.e., 4096 edges) would occur with a spacing of exactly 360°/4096. Due to electrical and geometric tolerances, however, these edge positions shift.

Decisive for the quality of an encoder is the deviation of the edge positions as this directly determines the position accuracy of a drive.
If one defines the first detected edge as 0°, all other edges would ideally follow with a spacing of exactly 360°/4096. The deviations from these target values (each relative to the first detected edge)

are recorded over multiple revolutions. From these values, an average position deviation can be calculated for each edge.

Based on standard ISO 230-2, the **average position accuracy** of an encoder is defined as half the peak-to-peak value of the resulting average position error curve (Figure 7, red curve).

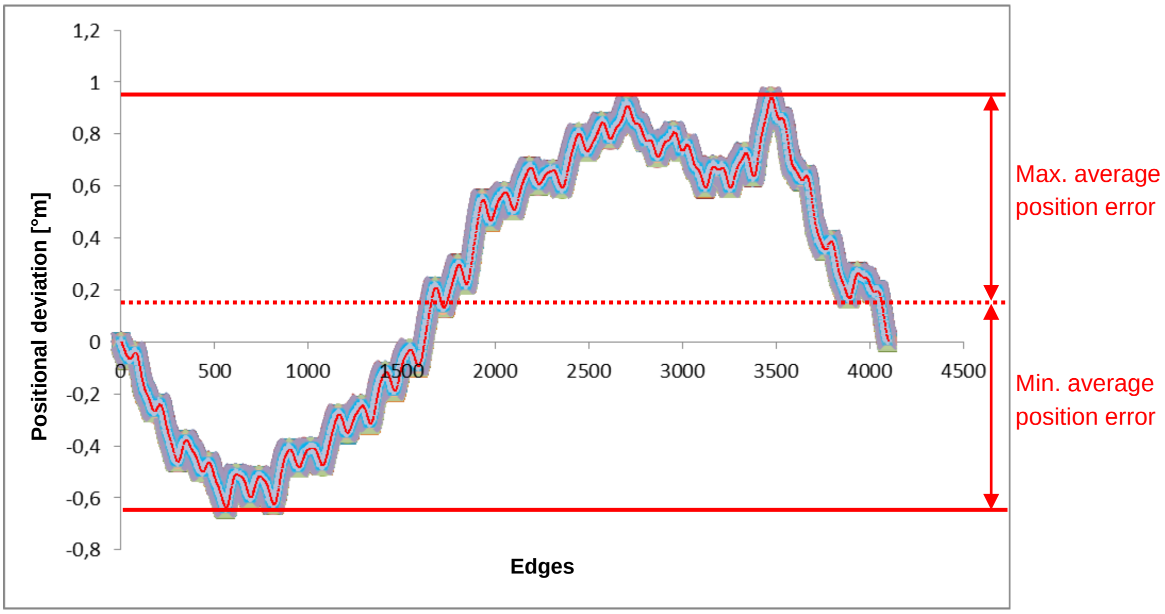

Figure 7: Position error curve of an IEH2-1024 encoder over one revolution, measured 25 times

The encoder with the position error curve shown in Figure 7 thus has an average position accuracy of approx. ±0.75°. A relative positioning of, e.g., one half revolution can thereby lead to a total error of twice the maximum position error under certain circumstances.

Note: For an incremental encoder without reference position, the absolute error of a given edge is not known, since no absolute position information is available. The position of the error curve over the x-axis (time, angle) is not defined and may vary from measurement to measurement.

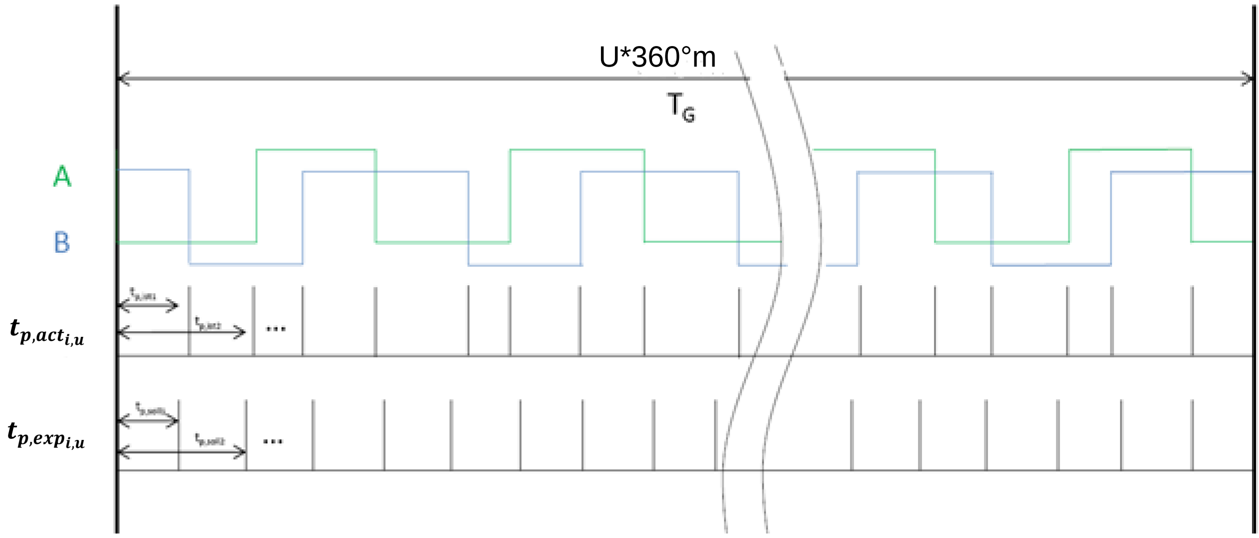

Figure 8: Explanation of the calculation of the position error

Definitions

U		*Number of recorded revolutions*
I		*Pulse number of the encoder*
$\Delta p_{i,u}$	$[°m]$	*Position error of a given edge i in the measured revolution u (relative to a complete revolution)*
$\Delta \bar{p}_i$	$[°m]$	*Average position error of an edge i*
Pos_{Error}	$[°m]$	*Average position accuracy (±x°) of the encoder for a direction of rotation*
$t_{p,act_{i,u}}$	$[s]$	*Actual time of an edge i in the measured revolution u relative to the starting point (first sampled edge, 0°)*
$t_{p,exp_{i,u}}$	$[s]$	*Expected time of an edge i relative to the starting point. The target times can be generated via a reference encoder or the time of a revolution (360°m, T_G) can be measured (assumes ideal concentricity of the motor)*
T_G	$[s]$	*Time for the number of measured revolutions (U*360°m). This can be measured via a reference encoder or using the time*

The single position errors are calculated according to formula 6:

$$\boldsymbol{\Delta p_{i,u} = \frac{t_{p,act_{i,u}} - t_{p,exp_{i,u}}}{T_G} * U * 360°}$$ **Formula 6**

with
$i = 1..4 * I$ and $u = 1..U$

This yields the average position deviations of each edge:

$$\Delta\bar{p}_i = \frac{1}{U} * \sum_{u=1}^{U} \Delta p_{i,u}$$ **Formula 7**

The average position accuracy of an encoder is calculated as half the difference between the maximum and minimum average deviation (formula 8).

$$Pos_{Error} = \pm \frac{max(\Delta\bar{p}_i) - min(\Delta\bar{p}_i)}{2}$$ **Formula 8**

Repeatability

If a position is approached multiple times (from the same direction), the respective edge is in reality generated at a somewhat different position each time. Causes for this include, among other things, mechanical tolerances of the attachment system as well as the signal noise.
A statistical measure that specifies the range in which the position of an edge can spread with a certain probability is the so-called repeatability.
To determine this parameter, the actual positions of the edges are first recorded over several revolutions. For each edge, the difference between all of its measured actual positions is then calculated. This is shown schematically for the first iterations in Figure 9.

Flanks / Re-volution	1	2	3	. . .	4096
1	0°	0,000862°	-0,000723°	. . .	-0,001064°
2	-0,000494°	0,000880°	0,000598°	. . .	0,001056°
3	0,001006°	0,000087°	0,000243°	. . .	-0,001336°
⋮	⋮	⋮	⋮	. . .	⋮
25	-0,000663°	-0,000315°	0,000422°	...	-0,001296°

Figure 9: Matrix with actual positions of an IEH2-1024 encoder measured over 25 revolutions

Assuming that the resulting deviations Δp_W for each individual edge have an approximately normal distribution, the standard deviation of the normal distribution can be determined from all available values as a whole (formula 9).

N		*Number of available measured values*
U		*Number of recorded revolutions*
s	$[°m]$	*Standard deviation*
Δp_{w_n}	$[°m]$	*Position deviation of the actual position of an edge to the actual position of one of its repeating edges*
$\Delta\bar{p}_w$	$[°m]$	*Average value of Δp_{w_n}*

W	$[°m]$	*Repeatability **for one direction of rotation** of the motor*

$$s = \sqrt{\frac{1}{N-1}\sum_{n=1}^{N}\left(\Delta p_{w_n} - \Delta\overline{p}_w\right)^2}$$ **Formula 9**

With $n = 1 \ldots N$ *and* $N = \frac{U*(U-1)}{2} * 4 * I$ *(for U=25 and I=1024:* $N \approx 1.2\ million$ *measurement values).*

The repeatability then corresponds to 6x the standard deviation (6 sigma). The limits within which the position of an edge can lie can thereby be statistically ensured with a sufficiently high probability.

$$W = 6 * s$$ **Formula 10**

Shown in Figure 10 in the form of a histogram is a typical distribution for the repeatability of an encoder. The repeatability in this case is approx. 0.027° (±0.0135°). The deviations between the actual positions of an edge are, thus, located in this range with a probability of 99.7%.

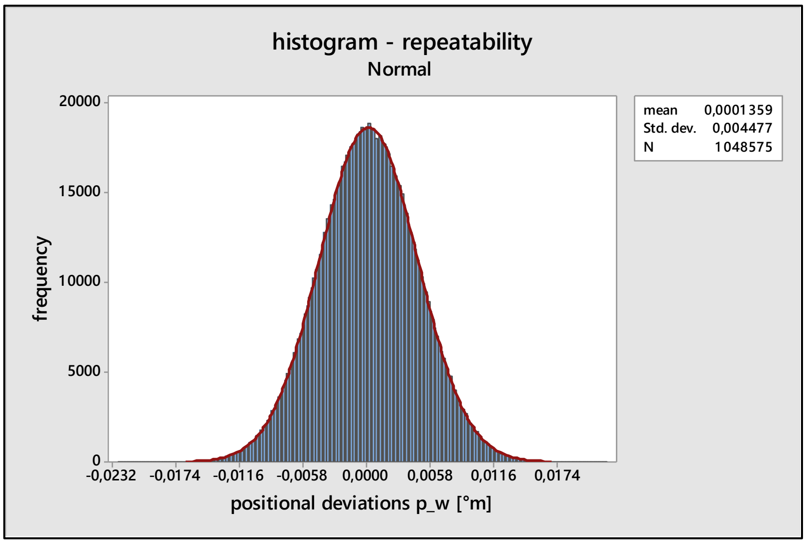

Figure 10: Distribution of the position deviations Δp_F

Note: If the target and actual times of the edges are ascertained for determining the position deviations using a time measurement, non-ideal concentricity of the motor may lead to measurement uncertainties for the repeatability.

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