MAQ473

9-Bit to 14-Bit, MagAlpha Automotive Angle Sensor with ABZ Incremental and PWM Outputs

DESCRIPTION

The MAQ473 detects the absolute angular position of a permanent magnet, typically a diametrically magnetized cylinder on a rotating shaft. Fast data acquisition and processing provide accurate angle measurement at speeds from 0rpm to 60,000rpm.

The MAQ473 supports a wide range of magnetic field strengths and spatial configurations. Both end-of-shaft and off-axis (side-shaft mounting) configurations are supported.

The MAQ473 features magnetic field strength detection with programmable thresholds to allow sensing of the magnet position relative to the sensor for creation of functions such as the sensing of axial movements or for diagnostics.

The on-chip non-volatile memory provides storage for configuration parameters, including the reference zero-angle position, ABZ encoder settings, and magnetic field detection thresholds.

The MAQ473 is AEC-Q100 qualified, and is available in a QFN-16 (3mmx3mm) package.

FEATURES

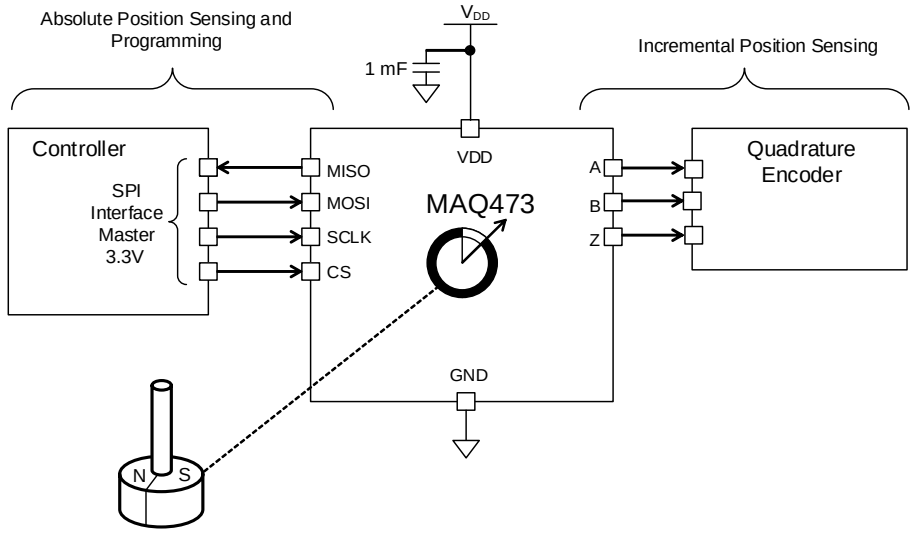
- 9-Bit to 14-Bit Resolution Absolute Angle Encoder
- Contactless Sensing for Long Lifespan
- SPI Serial Interface with Parity Bit for Angle Readout and Chip Configuration
- Configuration Programmable Magnetic Field Strength Detection for Diagnostic Checks
- Incremental 12-Bit ABZ Quadrature Encoder Interface with Programmable Pulses Per Turn from 1 to 1024
- 14-Bit PWM Output
- 3.3V, 12mA Supply Current
- -40°C to +150°C Operating Temperature
- Available in a QFN-16 (3mmx3mm) Package with Wettable Flanks
- Available in AEC-Q100 Grade 1

APPLICATIONS

- Automotive
- Angle Encoders
- Automotive Angle or Speed Sensors
- Robotics

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TYPICAL APPLICATION



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ORDERING INFORMATION

Part Number*	Package	Top Marking	MSL Rating
MAQ473GQE-AEC1	QFN-16 (3mmx3mm)	*See Below*	1

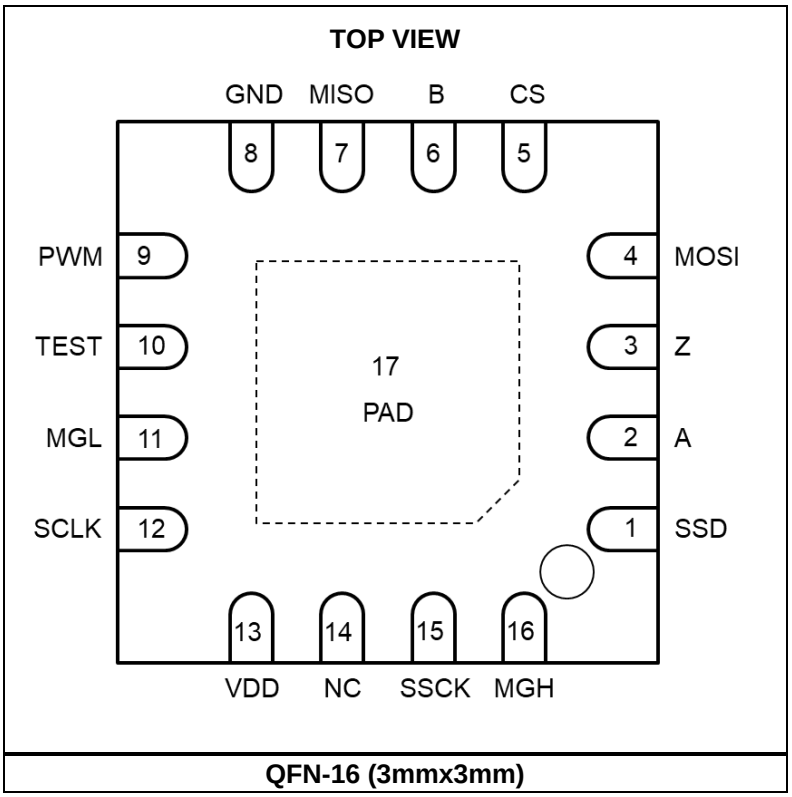
* For Tape & Reel, add suffix -Z (e.g. MAQ473GQE–AEC1-Z).

TOP MARKING

BNXY
LLLL

BNX: Product code of MAQ473GQE
Y: Year code
LLLL: Lot number

PACKAGE REFERENCE



QFN-16 (3mmx3mm)

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PIN FUNCTIONS

Pin #	Name	Description
1	SSD	**Data out (SSI).**
2	A	**Incremental output.**
3	Z	**Incremental output.**
4	MOSI	**Data in (SPI).** The MOSI pin has an internal pull-down resistor.
5	CS	**Chip select (SPI).** The CS pin has an internal pull-up resistor.
6	B	**Incremental output.**
7	MISO	**Data out (SPI).** MISO has an internal pull-down resistor that is enabled when the device is in a high-impedance state.
8	GND	**Supply ground.**
9	PWM	**PWM output**.
10	TEST	**Connect to ground.**
11	MGL	**Digital output indicating field strength below the MGLT level.**
12	SCLK	**Clock (SPI).** The SCLK pin has an internal pull-down resistor.
13	VDD	**3.3V supply.**
14	NC	**No connection.** Leave the NC pin unconnected.
15	SSCK	**Clock (SSI).** The SSCK pin has an internal pull-down resistor.
16	MGH	**Digital output indicating field strength above the MGHT level.**
17	Exposed pad	**Recommend not to solder.** Leave floating.

ABSOLUTE MAXIMUM RATINGS (1)

Supply voltage .....-0.5V to +4.6V
Input pin voltage (V_I) .....-0.5V to +6.0V
Output pin voltage (V_O) .....-0.5V to +4.6V
Continuous power dissipation (T_A = 25°C) (2) 2.0W
Junction temperature .....160°C
Lead temperature .....260°C
Storage temperature..... -65°C to +160°C

ESD Ratings

Human body model (HBM) 2kV
Charged device model (CDM) 750V

Thermal Resistance (3)	θ_{JA}	θ_{JC}
QFN-16 (3mmx3mm)	50	12	°C/W

Notes:

1) Exceeding these ratings may damage the device.
2) The maximum allowable power dissipation is a function of the maximum junction temperature T_J (MAX), the junction-to-ambient thermal resistance θ_{JA}, and the ambient temperature T_A. The maximum allowable continuous power dissipation at any ambient temperature is calculated by P_D (MAX) = (T_J (MAX) - T_A) / θ_{JA}.
3) Measured on JESD51-7, 4-layer PCB.

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ELECTRICAL CHARACTERISTICS

Parameter	Symbol	Condition	Min	Typ	Max	Units
Recommended Operating Conditions						
Supply voltage	V_{DD}		3.0	3.3	3.6	V
Supply current	I_{DD}	From -40°C to +125°C	10.2	12	13.8	mA
Operating (ambient) temperature	T_A		-40		+150	°C
Applied magnetic field	B		30	60		mT

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GENERAL CHARACTERISTICS

V_{DD} = 3.3V, 45mT < B < 100mT, T_A = -40°C to +125°C, unless otherwise noted.

Parameter	Symbol	Condition	Min	Typ	Max	Units
Absolute Output (Serial)						
Effective resolution (±3σ)		filter window τ = 64µs	9.0	9.8	10.5	bits
		filter window τ = 16ms	13.0	13.8	14.5	bits
Noise root mean square (RMS)		filter window τ = 64µs	0.04	0.07	0.12	deg
		filter window τ = 16ms	0.003	0.004	0.007	deg
Refresh rate			850	980	1100	kHz
Data output length			16		16	bits
Response Time						
Start-up time (4)		filter window τ = 64µs			0.6	ms
		filter window τ = 16ms			260	ms
Latency (4)		Constant speed propagation delay	8		10	µs
Filter cutoff frequency (4)	f_{CUTOFF}	filter window τ = 64µs		6		kHz
	f_{CUTOFF}	filter window τ = 16ms		23		Hz
Accuracy						
Integral nonlinearity (INL) at 25°C		At room temperature across the full field range		0.7		deg
INL between -40°C and +125°C (5)		Across the full temperature range and field range		1.1		deg
INL at 150°C		Across the full field range		1.16		deg
Output Drift						
Temperature-induced drift at room temperature (5)				0.015		deg/°C
Temperature-induced variation (5)		From 25°C to 85°C		0.5		deg
		From 25°C to 125°C		1.0		deg
Magnetic field induced (5)				0.005		deg/mT
Voltage supply induced (5)					0.3	deg/V
Absolute Output (PWM)						
PWM frequency	f_{PWM}		840	970	1090	Hz
PWM resolution			13	13.8	14.0	bits
Incremental Output (ABZ)						
ABZ update rate				16		MHz
Resolution (edges per turn)		Programmable	4		4096	
Pulses per channel per turn	PPT + 1	Programmable	1		1024	
ABZ hysteresis (5)	H	Programmable	0.08		2.8	deg
Systematic jitter (5)		For PPT = 1023, up to 60mT			11	%
		For PPT = 127			7	%

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GENERAL CHARACTERISTICS *(continued)*

V_{DD} = 3.3V, 45mT < B < 100mT, T_A = -40°C to +125°C, unless otherwise noted.

Parameter	Symbol	Condition	Min	Typ	Max	Units
Magnetic Field Detection Thresholds						
Accuracy (5)				5		mT
Hysteresis (5)	MagHys			6		mT
Temperature drift (5)				-600		ppm/°C
Digital I/O						
Input high voltage	V_{IH}		2.5		5.5	V
Input low voltage	V_{IL}		-0.3		+0.8	V
Output low voltage (5)	V_{OL}	I_{OL} = 4mA			0.4	V
Output high voltage (5)	V_{OH}	I_{OH} = 4mA	2.4			V
Pull-up resistor	R_{PU}		46	66	97	kΩ
Pull-down resistor	R_{PD}		43	55	97	kΩ
Rising edge slew rate (4)	t_R	CL = 50pF		0.7		V/ns
Falling edge slew rate (4)	t_F	CL = 50pF		0.7		V/ns

Notes:

4) Guaranteed by design.
5) Guaranteed by characterization.

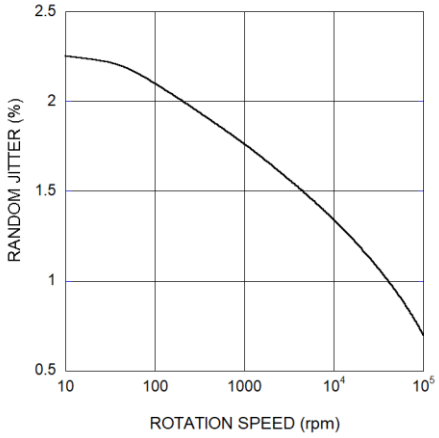
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TYPICAL CHARACTERISTICS

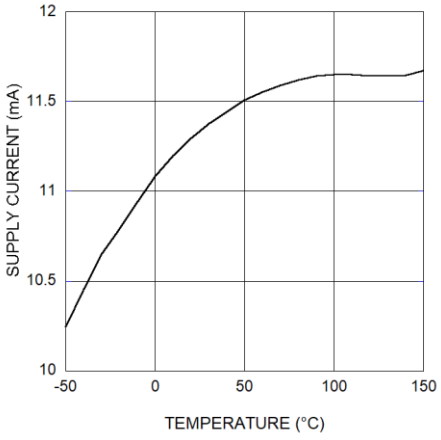
V_{DD} = 3.3V, T_A = 25°C, unless otherwise noted.

ABZ Jitter

PPT = 255, τ = 1ms

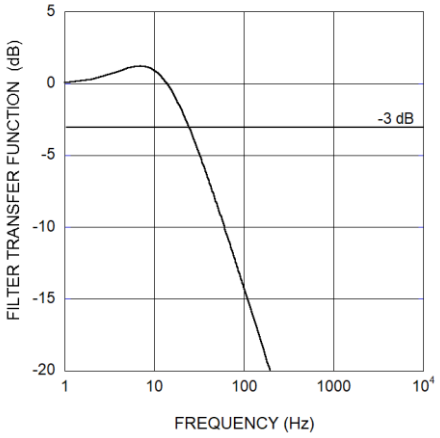


Current Consumption



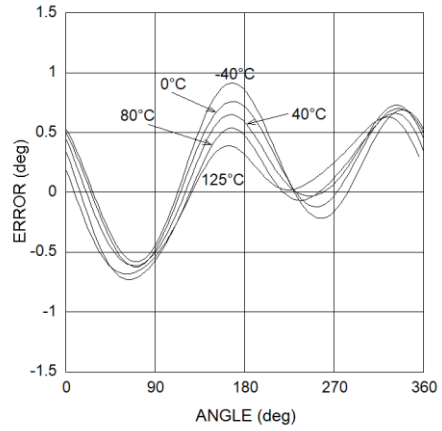
Filter Transfer Function

τ = 16ms

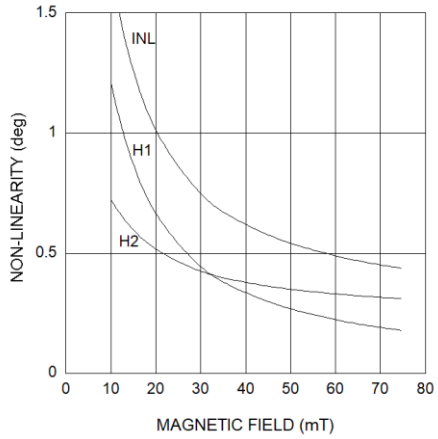


Error Curve

50mT

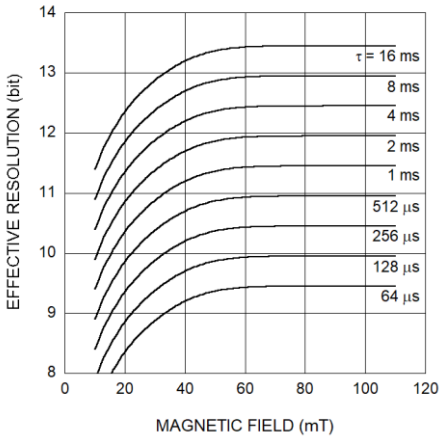


Nonlinearity (INL and Harmonics)



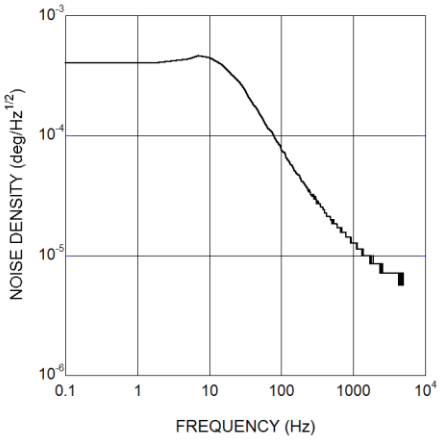
Effective Resolution

3σ



Noise Spectrum

50mT and τ = 16ms



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FUNCTIONAL BLOCK DIAGRAM

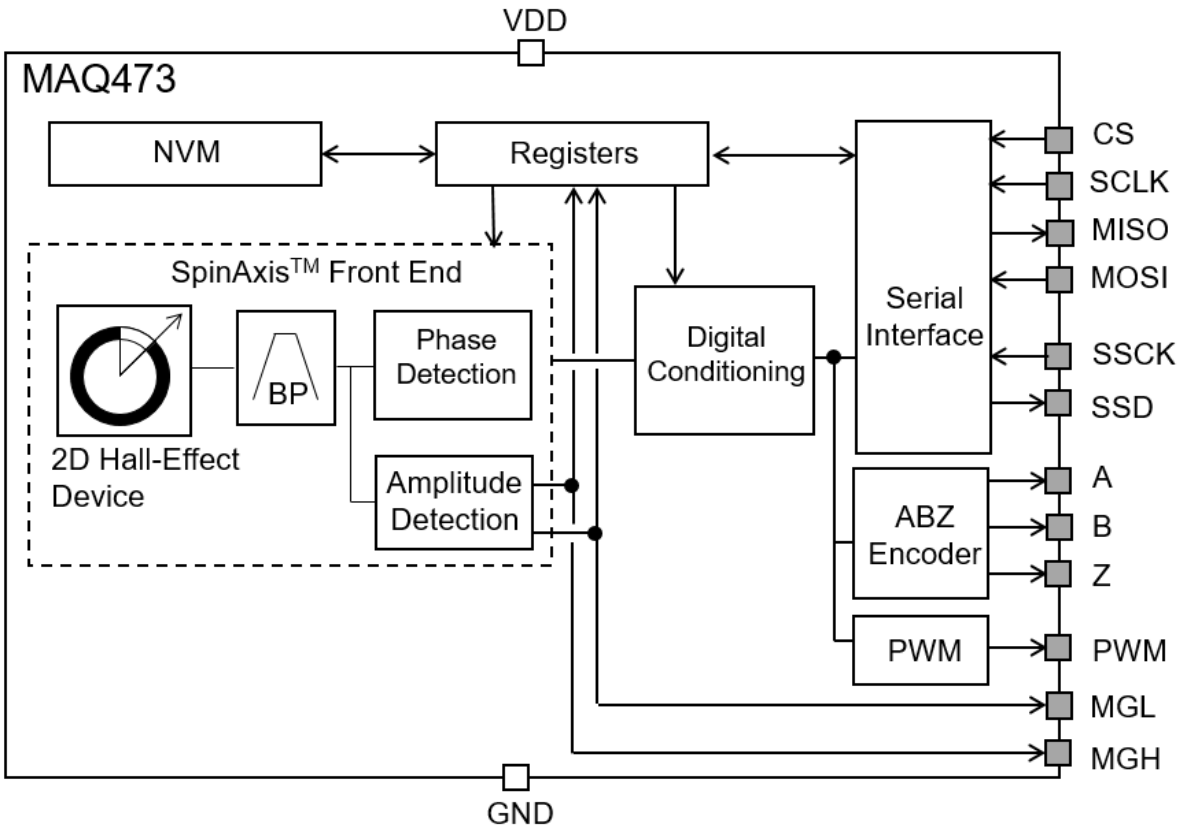


Figure 1: Functional Block Diagram

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OPERATION

Sensor Front End

The magnetic field is detected with integrated Hall devices located in the center of the package. The angle is measured using MPS's proprietary SpinAxis™ method, which directly digitizes the direction of the field without the need for complex arctangent computation or feedback loop-based circuits (interpolators).

The SpinAxis™ method is based on phase detection, and generates a sinusoidal signal with a phase that represents the angle of the magnetic field. The angle is then obtained by a time-to-digital converter, which measures the time between the zero crossing of the sinusoidal signal and the edge of a constant waveform (see Figure 2). The time-to-digital is outputted from the front end to the digital conditioning block.

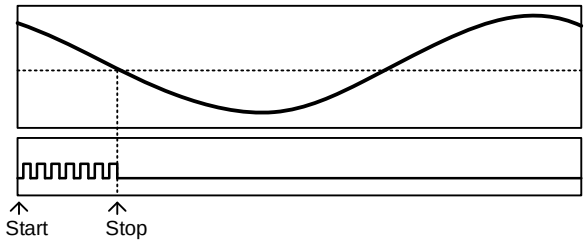


Figure 2: Phase Detection Method across the Sine Waveform (Top) and Time-to-Digital Converter Clock (Bottom)

The output of the front end delivers a digital number proportional to the angle of the magnetic field at the rate of 1MHz in a straightforward, open-loop manner.

Digital Filtering

The front-end signal is further treated to achieve the final effective resolution. This treatment does not add any latency in steady conditions. The filter transfer function can be calculated with Equation (1):

$$H(s) = \frac{1+2\tau s}{(1+\tau s)^2} \quad (1)$$

Where τ is the filter time constant related to the cutoff frequency by: $\tau = 0.38 / f_{CUTOFF}$.

See the General Characteristics section on page 5 for the value of f_{CUTOFF}.

Sensor Magnet Mounting

The MAQ473's sensitive area (where the Hall devices are placed) is confined within a region less than 100µm wide and has multiple integrated Hall devices. This volume is located both horizontally and vertically within 50µm of the center of the QFN package. The sensor detects the angle of the magnetic field projected in a plane parallel to the package's upper surface. This means that the only relevant magnetic field is the in-plane component (X and Y components) in the mid-point of the package.

By default, when looking at the top of the package, the angle increases when the magnetic field rotates clockwise. Figure 3 shows the zero angle of the unprogrammed sensor, where the plus sign indicates the sensitive point. Both the rotation direction and the zero angle can be programmed.

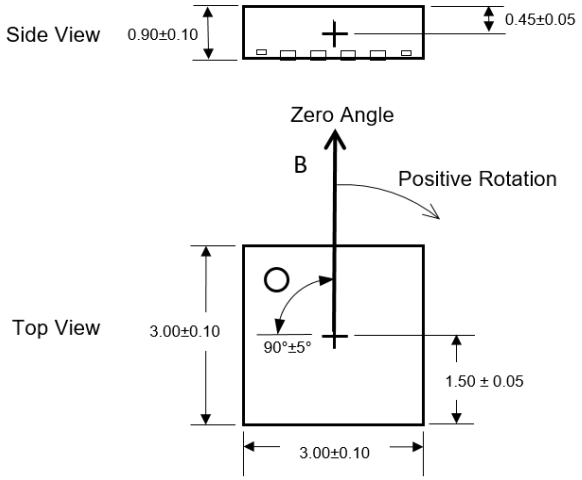


Figure 3: Detection Point and Default Positive Direction

This type of detection provides flexibility for angular encoder design. The sensor only requires the magnetic vector to lie within the sensor plane with a field amplitude of at least 30mT. The MAQ473 can work with fields smaller than 30mT, but the linearity and resolution performance may deviate from the specifications. The most straightforward mounting method is to place the MAQ473 sensor on the rotation axis of a permanent magnet (e.g. a diametrically magnetized cylinder) (see Figure 4 on page 10).

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The recommended magnet is a Neodymium alloy (N35) cylinder with dimensions Ø5x3mm, inserted into an aluminum shaft with a 1.5mm air gap between the magnet and the sensor (surface of package). For good linearity, position the with a precision of 0.5mm.

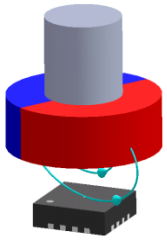


Figure 4: End-of-Shaft Mounting

If the end-of-shaft position is not available, the sensor can be positioned away from the rotation axis of a cylinder or ring magnet (see Figure 5). In this case, the magnetic field angle is not directly proportional to the mechanical angle. The MAQ473 can be adjusted to compensate for this effect and recover the linear relation between the mechanical angle and the sensor output. With multiple pole pair magnets, the MAQ473 indicates multiple rotations for each mechanical turn.

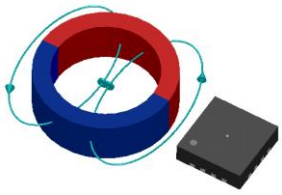


Figure 5: Side-Shaft Mounting

Electrical Mounting and Power Supply Decoupling

It is recommended to place a 1µF decoupling capacitor close to the sensor with a low-impedance path to GND (see Figure 6).

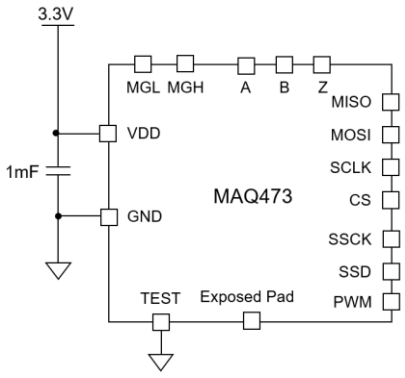


Figure 6: Supply Decoupling Connection

In general, the MAQ473 works well with or without the exposed pad connected. For optimum electrical, thermal, and mechanical conditions, it is recommended that the exposed pad be connected to ground.

Serial Interface

The sensor supports the serial peripheral interface (SPI) standard for angle reading and register programming. Alternatively, the synchronous serial interface (SSI) bus can be used for angle reading (programming through the SSI is not supported).

The data length is 16 bits. For checking the integrity of the data received (angle or register content) the master sends a 17th clock count and receives a parity bit.

SPI

The SPI is a four-wire, synchronous, serial communication interface. The MAQ473 supports SPI Mode 3 and Mode 0 (see Table 1 and Table 2). The SPI mode (0 or 3) is detected automatically by the sensor, and therefore does not require any action from the user. The maximum clock rate supported on the SPI is 25MHz. There is no minimum clock rate. Real-world data rates depend on the PCB layout quality and signal trace length. See Figure 7 and Table 3 on page 11 for SPI timing.

Table 1: SPI Specification

	Mode 0	Mode 3
SCLK Idle State	Low	High
Data Capture	On SCLK rising edge	
Data Transmission	On SCLK falling edge	
CS Idle State	High	
Data Order	MSB first	

Table 2: SPI Standard

	Mode 0	Mode 3
CPOL	0	1
CPHA	0	1
Data Order (DORD)	0 (MSB first)	

All commands to the MAQ473 (whether for writing or reading register content) must be transferred through the SPI MOSI pin and must be 16 bits long.

See the SPI Communication section on page 12 for details.

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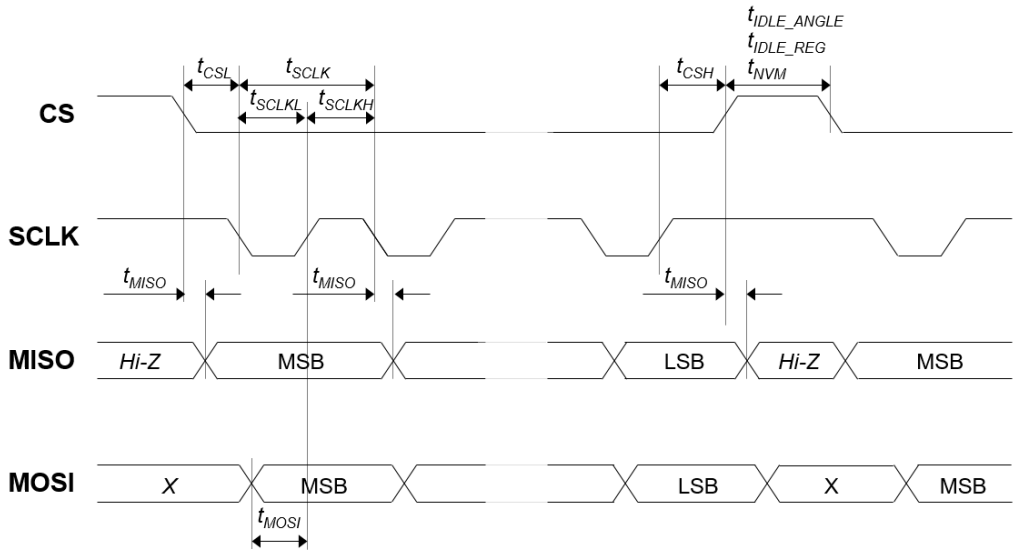


Figure 7: SPI Timing Diagram

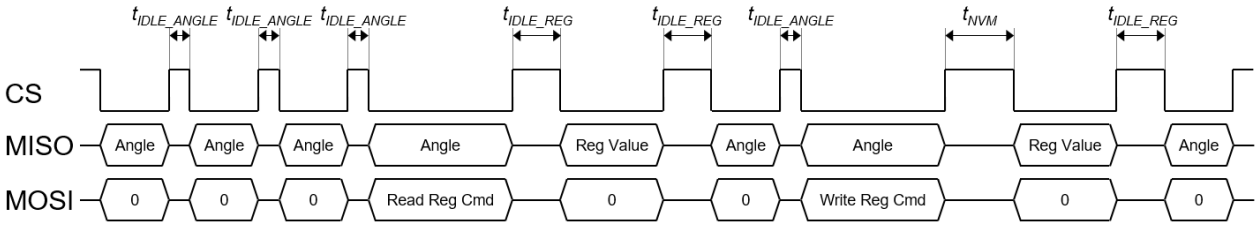


Figure 8: Minimum Idle Time

Table 3: SPI Timing

Parameter (6)	Description	Min	Max
t_{IDLE_ANGLE}	Idle time between two subsequent angle transmissions	150ns	-
t_{IDLE_REG}	Idle time before and after a register readout	750ns	-
t_{NVM}	Idle time between a write command and a register readout (delay necessary for non-volatile memory update)	20ms	-
t_{CSL}	Time between the CS falling edge and SCLK falling edge	80ns	-
t_{SCLK}	SCLK period	40ns	-
t_{SCLKL}	Low level of SCLK signal	20ns	-
t_{SCLKH}	High level of SCLK signal	20ns	-
t_{CSH}	Time between SCLK rising edge and CS rising edge	25ns	-
t_{MISO}	SCLK setting edge to data output valid	-	15ns
t_{MOSI}	Data input valid to SCLK reading edge	15ns	-

Note:

6) Guaranteed by design.

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SPI Communication

The sensor supports three types of SPI operation:

- Read angle
- Read configuration register
- Write configuration register

Each operation has a specific frame structure, described below.

SPI Read Angle

Every 1µs, new data is transferred into the output buffer. The master device triggers the reading by pulling CS low.

When a trigger event is detected, the data remains in the output buffer until the CS signal is de-asserted (see Table 4).

Table 4: Sensor Data Timing

Event	Action
CS falling edge	Start reading and freeze the output buffer
CS rising edge	Release the output buffer

Figure 9 shows a diagram of a full SPI angle reading. Figure 10 shows a partial SPI angle reading. A full angle reading requires 16 clock pulses. The sensor MISO line returns:

	MSB															*LSB*
MISO	***Angle[15:0]***															
MOSI	***0***															

The MagAlpha family has sensors with different features and levels of resolution. See the data output length section in the General Characteristics section on page 5 for the number of useful bits delivered at the serial output. If the data length is less than 16, the rest of the bits sent are 0s. For example, a data output length of 12 bits means that the serial output delivers a 12-bit angle value with 4 bits of 0s padded at the end (the MISO state remains 0). If the master sends 16 clock counts, the MAQ473 replies with:

	MSB															*LSB*
MISO	***Angle[15:4]***												***0***	***0***	***0***	***0***
MOSI	***0***															

Angle reading can be therefore optimized without any loss of information by reducing the number of clock counts. In the case of a 12-bit data output length, only 12 clock counts are required to get the full sensor resolution.

	MSB															*LSB*
MISO	***Angle[15:4]***															
MOSI	***0***															

If less resolution is needed, the angle can be read by sending even fewer clock counts (since the MSB is first).

In case of fast reading, the MAQ473 continues sending the same data until the data is refreshed. See the refresh rate section in the General Characteristics section on page 5.

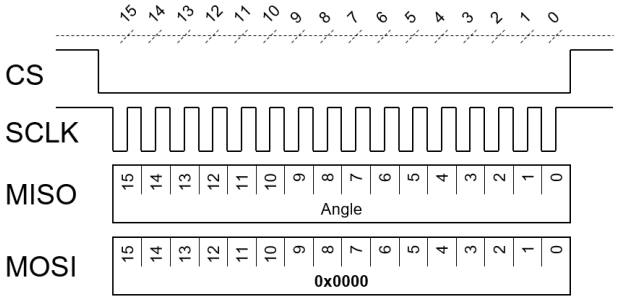


Figure 9: Full 16-Bit SPI Angle Reading Diagram

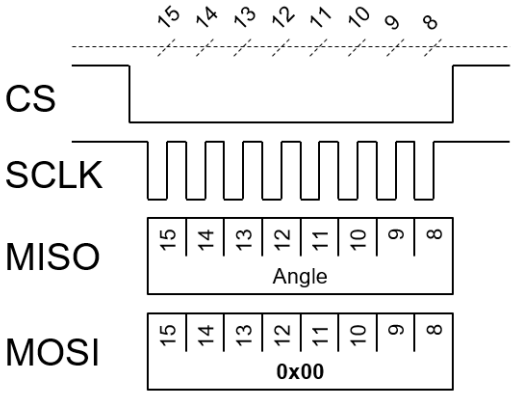


Figure 10: Partial 8-Bit SPI Angle Reading Diagram

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SPI Read Register

A read register operation consists of two 16-bit frames. The first frame sends a read request, which contains the 3-bit read command (010) followed by the 5-bit register address. The last 8 bits of the frame must all be set to 0. The second frame returns the 8-bit register value (MSB byte).

First 16-bit SPI frame (read request):

	MSB															LSB
MISO	Angle[15:0]															
	Command			Reg. Address												
MOSI	0	1	0	A_4	A_3	A_2	A_1	A_0	0	0	0	0	0	0	0	0

Second 16-bit SPI frame (response):

	Register Value															
MISO	V_7	V_6	V_5	V_4	V_3	V_2	V_1	V_0	0	0	0	0	0	0	0	0
	MSB															LSB
MOSI	0															

Figure 11 shows a complete transmission overview.

For example, to get the value of the magnetic level high and low flags (MGH and MGL), read register 27 (bit[6], bit[7]) by sending the following first frame:

	MSB															LSB
MISO	Angle[15:0]															
	Command			Reg. Address												
MOSI	0	1	0	1	1	0	1	1	0	0	0	0	0	0	0	0

In the second frame, the MagAlpha replies:

	Register Value															
MISO	MGH	MGL	X	X	X	X	X	X	0	0	0	0	0	0	0	0
	MSB															LSB
MOSI	0															

Figure 12 shows a complete example overview.

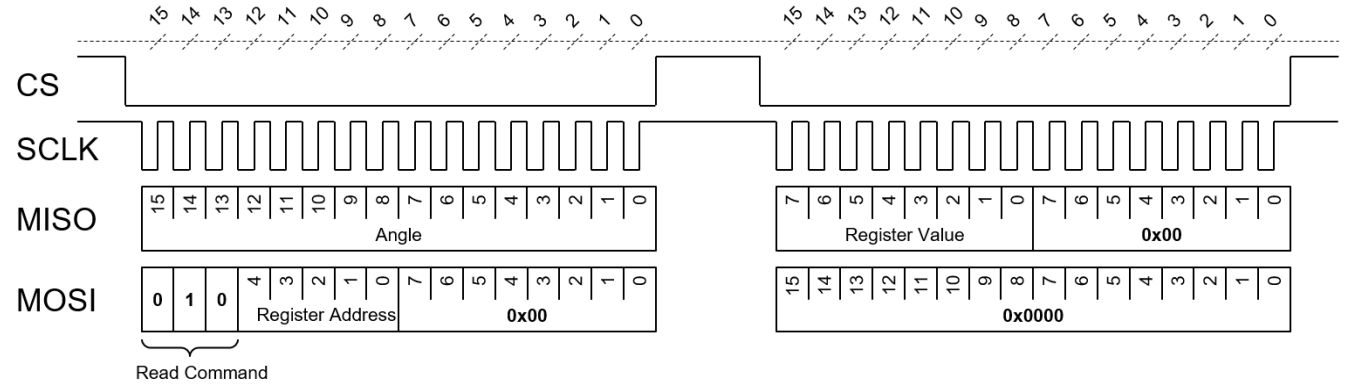


Figure 11: Two 16-Bit Frames Read Register Operation

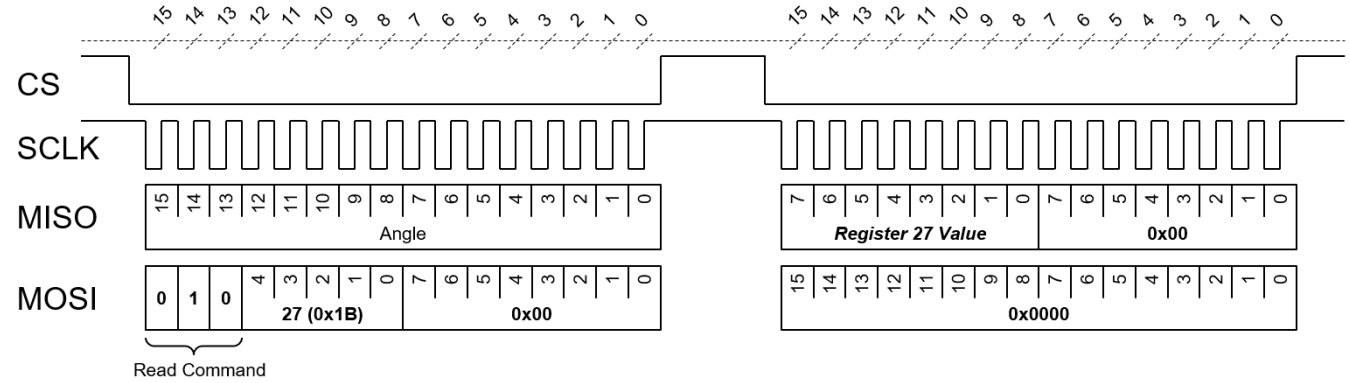


Figure 12: Example Read Magnetic Level Flags High and Low (MGH, MGH) on Register 27, Bits[6:7]

SPI Write Register

The Register Map section on page 18 shows the programmable 8-bit registers. Data written to these registers is stored in the on-chip non-volatile memory (NVM) and reloaded automatically at start-up.

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A write register operation consists of two 16-bit frames. The first frame sends a write request, which contains the 3-bit write command (100), followed by the 5-bit register address and the 8-bit value (MSB first). The second frame returns the newly written register value (acknowledge).

The NVM is guaranteed to endure 1,000 write cycles at 25°C.

It is critical to wait 20ms between the first and the second frame. This is the time taken to write to the NVM. Failure to implement this wait period results in the register's previous value being read. Note that this delay is only required after a write request. A read register request or read angle does not require this wait time.

The first 16-bit SPI frame (write request) is:

	MSB															LSB
MISO	Angle[15:0]															

	Command			Reg. Address					Register Value							
MOSI	1	0	0	A_4	A_3	A_2	A_1	A_0	V_7	V_6	V_5	V_4	V_3	V_2	V_1	V_0

The second 16-bit SPI frame (response) is:

	Register Value															
MISO	V_7	V_6	V_5	V_4	V_3	V_2	V_1	V_0	0	0	0	0	0	0	0	0

	MSB															LSB
MOSI	0															

The readback register content can be used to verify the register programming. Figure 13 shows a complete transmission overview.

For example, to set the value of the output rotation direction (RD) to counterclockwise (high), write register 9 by sending the following first frame:

	MSB															LSB
MISO	Angle[15:0]															

	Command			Reg. Address					Register Value							
MOSI	1	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0

Send the second frame after a 20ms wait time. If the register is written correctly, the reply is:

	Register Value															
MISO	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	MSB															LSB
MOSI	0															

See Figure 14 for a complete example.

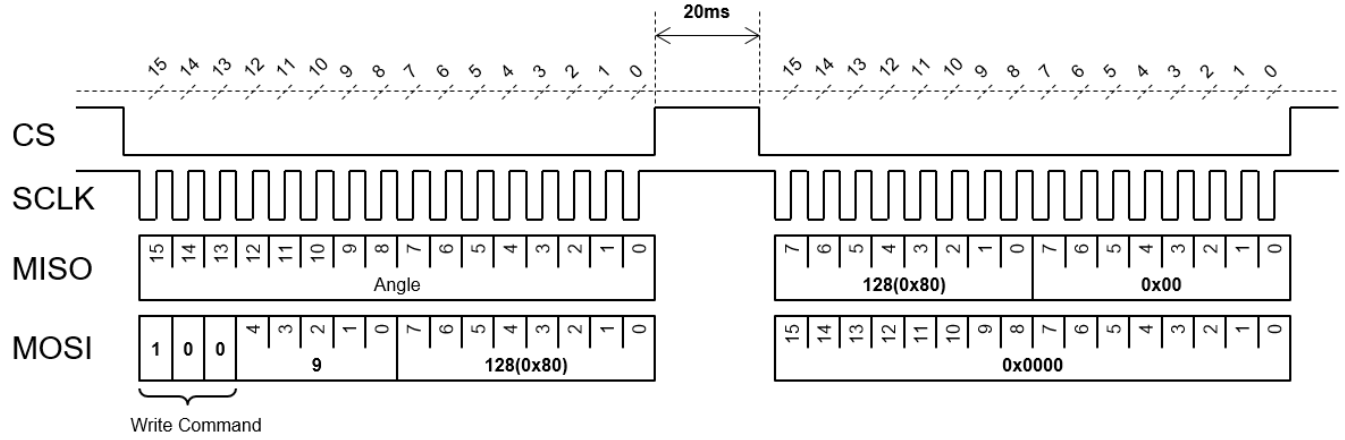


Figure 13: Overview of Two 16-Bit Frames Write Register Operation

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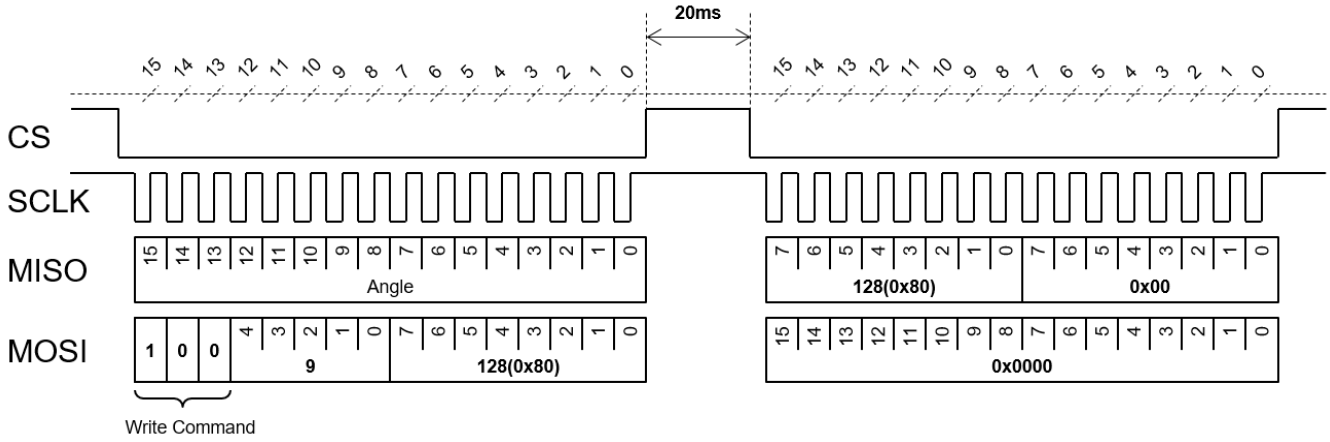


Figure 14: Example Write Output Rotation Direction (RD) to Counterclockwise (High), on Register 9, Bit 7

SSI

SSI is a two-wire, synchronous serial interface for data reading only. The sensor operates as a slave to the external SSI master and supports only angle reading. It is not possible to read or write registers via the SSI.

SSI Communication

Unlike the SPI, the sensor SSI only supports angle reading. It is not possible to read or write registers using the SSI. Figure 15 and Table of show the SSI timing communication details.

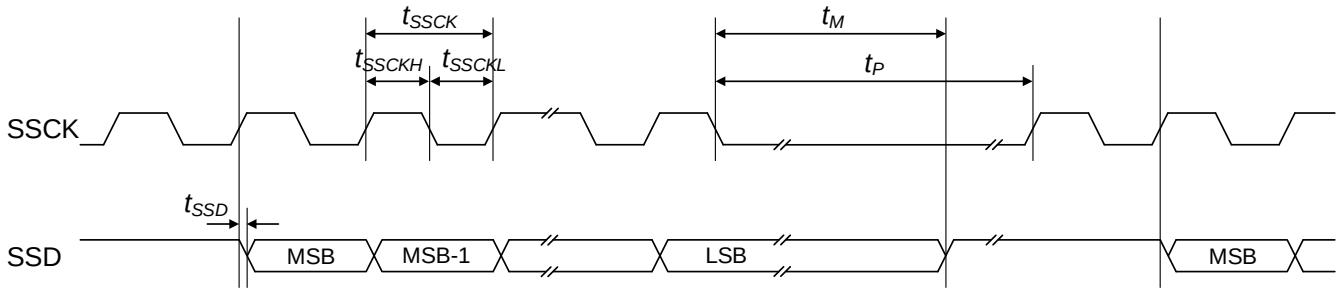


Figure 15: SSI Timing

Table 5: SSI Timing

Parameter	Description	Min	Max
t_{SSD}	Delay between the SSCK rising edge and the start of data transfer	-	15ns
t_{SSCK}	SSCK period	0.04µs	16µs
t_{SSCKL}	Low level of the SSCK signal	0.02µs	8µs
t_{SSCKH}	High level of the SSCK signal	0.02µs	8µs
t_M	Transfer timeout (monoflop time)	25µs	-
t_P	Dead time: SSCK high time for next data reading	40µs	-

SSI Read Angle

The bit order of the transmitted data is MSB first and LSB last. Every 1µs, new data is transferred into the output buffer. The master device triggers the reading by driving SSCK high. A full reading requires up to 17 clock counts (see Figure 16).

The first clock is a dummy clock to start the transmission. The data length is up to 16 bits long. See the data output length section in the General Characteristics section on page 5 for the number of useful bits delivered at the serial output.

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The first MSB are transmitted on the second clock count. If the data length is less than 16 bits, the 16-bit output word is completed by 0s. Therefore, the reading can also be performed with fewer than 16 clock counts. For example, for a part with a 12-bit data length, it is only necessary to send the first dummy clock to start the transmission + 12 clocks to read the angle data.

When a trigger event is detected, the data remains in the output buffer until the clock falling edge for the LSB bit = 0 and the transfer timeout time has passed (see Table 6).

Table 6: Sensor Data Timing

Trigger Event	Output Buffer Release
First SSCK pulse rising edge	SSCK falling edge + timeout t_M

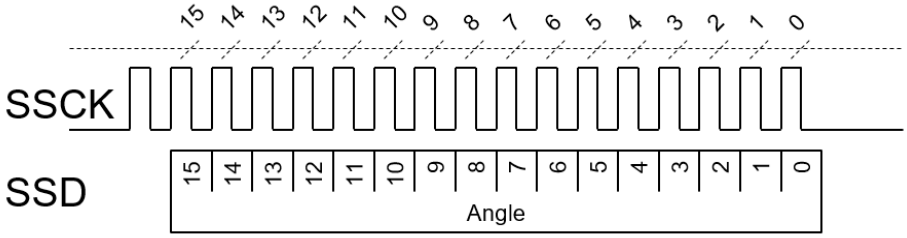


Figure 16: Diagram of a Full 16-Bit SSI Angle Reading (with First Dummy Clock)

Figure 17 shows the timing for consecutive angle readings.

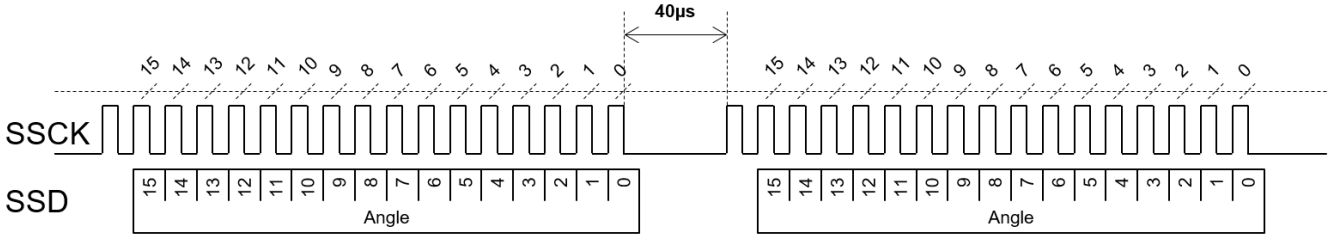


Figure 17: Diagram of Two Consecutive 16-Bit SSI Angle Readings with the Required Dead Time between the Frames

Parity Bit

The parity bit, or check bit, is added to the output string to ensure that the total number of 1s in the string is even. It is used as error detecting code for angle or register reading. The MAQ473 transmits the parity bit at the 17th clock edge (see Table 7 and Figure 18).

Table 7: Example of Parity Bit

16-Bit Output	Number of Bits Set to 1	Output with the Parity Bit
0000000000000000	0	00000000000000000**0**
1000110001100010	6	10001100011000100**0**
0101110100000000	5	01011101000000001

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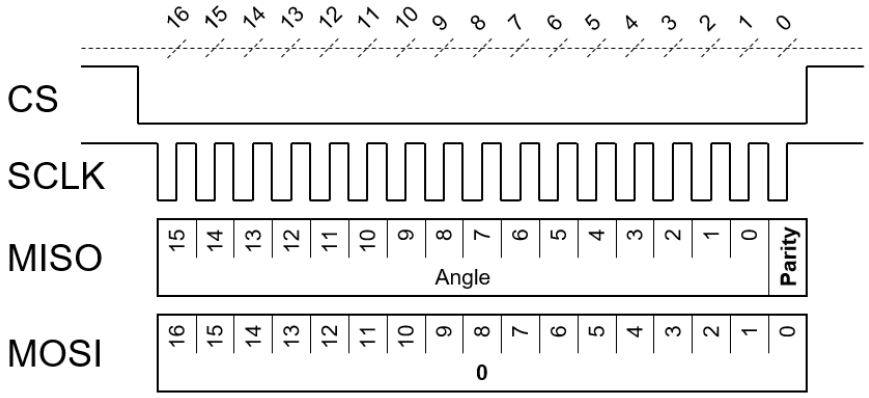


Figure 18: SPI Angle Reading with Parity Bit

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REGISTER MAP

Table 8: Register Map

# of Registers	Hex	Binary	Bit[7] (MSB)	Bit[6]	Bit[5]	Bit[4]	Bit[3]	Bit[2]	Bit[1]	Bit[0] (LSB)
0	0x0	00000	Z[7:0]							
1	0x1	00001	Z[15:8]							
2	0x2	00010	BCT[7:0]							
3	0x3	00011	-	-	-	-	-	-	ETY	ETX
4	0x4	00100	PPT[1:0]		ILIP[3:0]				-	-
5	0x5	00101	PPT[9:2]							
6	0x6	00110	MGLT[2:0]			MGHT[2:0]			-	-
9	0x9	01001	RD	-	-	-	-	-	-	-
14	0xE	01110	FW[7:0]							
16	0x10	10000	HYS[7:0]							
27	0x1B	11011	MGH	MGL	MIR[3:0]				-	-

Table 9: Factory Default Values

# of Registers	Hex	Binary	Bit[7] (MSB)	Bit[6]	Bit[5]	Bit[4]	Bit[3]	Bit[2]	Bit[1]	Bit[0] (LSB)
0	0x0	00000	0	0	0	0	0	0	0	0
1	0x1	00001	0	0	0	0	0	0	0	0
2	0x2	00010	0	0	0	0	0	0	0	0
3	0x3	00011	0	0	0	0	0	0	0	0
4	0x4	00100	1	1	0	0	0	0	0	0
5	0x5	00101	1	1	1	1	1	1	1	1
6	0x6	00110	0	0	0	1	1	1	0	0
9	0x9	01001	0	0	0	0	0	0	0	0
14	0xE	01110	0	1	1	1	0	1	1	1
16	0x10	10000	1	0	0	1	1	1	0	0

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Table 10: Programming Parameters

Parameters	Symbol	# of Bits	Description	See Table
Zero setting	Z	16	Sets the zero position	11
Bias current trimming	BCT	8	For side-shaft configuration: reduces the bias current of the X or Y Hall device	14
Enable trimming X	ETX	1	Biased current trimmed in the X-direction Hall device	15
Enable trimming Y	ETY	1	Biased current trimmed in the Y-direction Hall device	15
Pulses per turn	PPT	10	Number of pulses per turn of the ABZ output	19
Index length/position	ILIP	4	Parametrization of the ABZ index pulse	Figure 27
Magnetic field high threshold	MGHT	3	Sets the field strength high threshold	16
Magnetic field low threshold	MGLT	3	Sets the field strength low threshold	16
Rotation direction	RD	1	Determines the sensor positive direction	13
Filter window	FW	8	Size of the digital filter window	18
Hysteresis	HYS	8	ABZ output hysteresis	21

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REGISTER SETTINGS

Zero Setting

The MAQ473's zero position (a_0) can be programmed with 16 bits of resolution. The angle streamed out by the MAQ473 (a_{OUT}) is calculated with Equation (2):

$$a_{OUT} = a_{RAW} - a_0 \quad (2)$$

Where a_{RAW} is the raw angle provided by the MAQ473's front end.

The parameter Z[15:0], which is 0 by default, is the complementary angle of the zero setting. In decimals, it can be calculated with Equation (3):

$$a_0 = 2^{16} - Z[15:0] \quad (3)$$

Table 11 shows the zero-setting parameter.

Table 11: Zero-Setting Parameter

Z[15:0]	Zero Position a_0 (16-Bit Decimal)	Zero Position a_0 (deg)
0	65536	360.000
1	65535	359.995
2	65534	359.989
…	…	…
65534	2	0.011
65535	1	0.005

Example

To set the zero position to 20°, the Z[15:0] parameter must be equal to the complementary angle, and can be calculated with Equation (4):

$$Z[15:0] = 2^{16} - \frac{20°}{360°} 2^{16} = 61895 \quad (4)$$

In binary, it is written as 1111 0001 1100 0111.

Table 12 shows the content of registers 0 and 1.

Table 12: Register 0 and 1 Content

Reg	Bit[7]	Bit[6]	Bit[5]	Bit[4]	Bit[3]	Bit[2]	Bit[1]	Bit[0]
0	1	1	0	0	0	1	1	1
1	1	1	1	1	0	0	0	1

Rotation Direction

By default, when looking at the top of the package, the angle increases when the magnetic field rotates clockwise (CW) (see Figure 19 and Table 13).

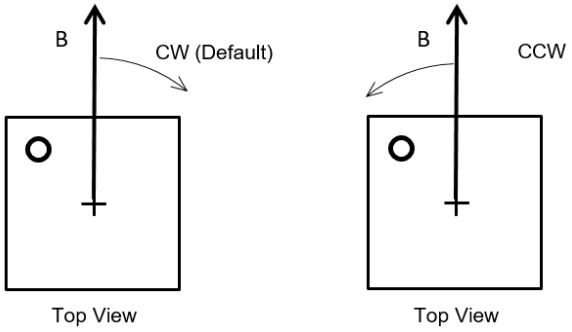


Figure 19: Positive Rotation Direction of the Magnetic Field

Table 13: Rotation Direction Parameter

RD	Positive Direction
0	Clockwise (CW)
1	Counterclockwise (CCW)

BCT Settings (Bias Current Trimming)

Side-Shaft

When the MAQ473 is mounted on the side of the magnet, the relationship between the field angle and the mechanical angle is no longer directly linear. This effect is related to the fact that the tangential magnetic field is usually smaller than the radial field. Calculate the field ratio (*k*) with Equation (5):

$$k = B_{RAD}/B_{TAN} \quad (5)$$

Where B_{RAD} and B_{TAN} are the maximum radial and tangential magnetic fields (see Figure 20).

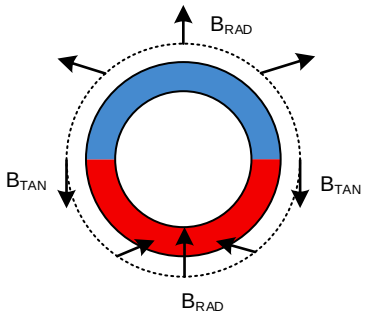


Figure 20: Side-Shaft Field

The *k* ratio depends on the magnet geometry and the distance to the sensor. Having a *k* ratio different than 1 results in the sensor output response not being linear with respect to the mechanical angle. Note that the error curve has the shape of a double sinewave (see Figure 22 on page 21). E is the amplitude of this error.

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The X-axis and Y-axis bias currents can be reduced by programming in order to recover an equal Hall signal for all angles, and therefore suppress the error. Parameter ETX and ETY control the direction in which sensitivity is reduced. The current reduction is set by the parameter bias current trimming register, BCT[7:0], which is an integer from 0 to 255.

In side-shaft configuration (i.e. the sensor center is located beyond the magnet's outer diameter), *k* is greater than 1. For optimum compensation, the sensitivity of the radial axis should be reduced by setting the BCT parameter, calculated with Equation (6):

$$BCT[7:0] = 258\left(1-\frac{1}{k}\right) \quad (6)$$

Figure 21 shows the optimum BCT value for a particular *k* ratio.

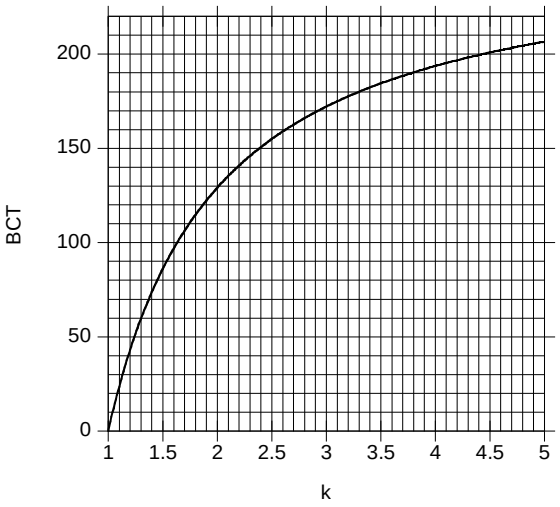


Figure 21: Relation between the *k* Ratio and the Optimum BCT to Recover Linearity

Table 14 shows some typical BCT values.

Table 14: Example of BCT Settings

E (deg)	Magnet Ratio *k*	BCT[7:0]
0	1.0	0
11.5	1.5	86
19.5	2.0	129
25.4	2.5	155
30.0	3.0	172
33.7	3.5	184
36.9	4.0	194
39.5	4.5	201
41.8	5.0	207

Determining k with the MagAlpha

It is possible to deduce the *k* ratio from the error curve obtained with the default BCT setting (BCT = 0). Rotate the magnet more than one revolution and record the output. Next, plot the error curve (the output minus the real mechanical position vs. the real mechanical position) and extract two parameters: the maximum error (E) and the position of this maximum with respect to a zero crossing a_M (see Figure 22). *k* can be calculated with Equation (7):

$$k = \frac{\tan(E + a_M)}{\tan(a_M)} \quad (7)$$

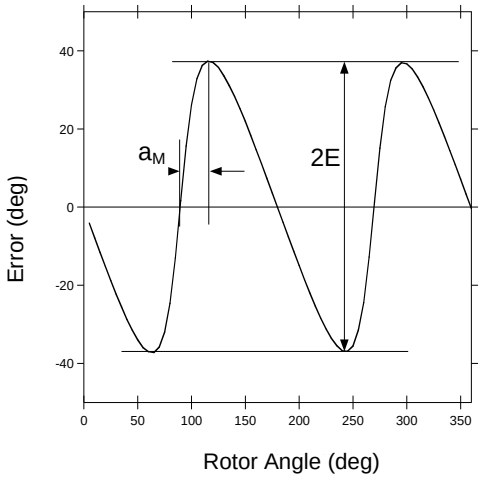


Figure 22: Error Curve in Side-Shaft Configuration with BCT = 0

Table 14 provides some examples. Alternatively, the *k* parameter can be obtained using Figure 23.

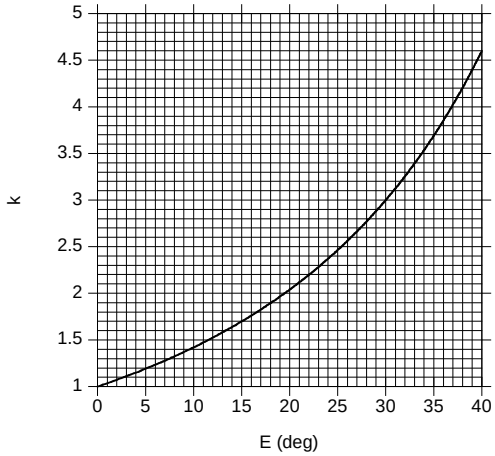


Figure 23: Relation between the Error Measured with BCT = 0 and the Magnet Ratio *k*

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Sensor Orientation

From the dot marked on the package, it is possible to know whether the radial field is aligned with sensor coordinate X or Y (see Figure 24).

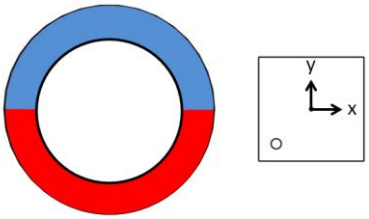


Figure 24: Package Top View with X- and Y-Axes

Determine which axis needs to be reduced based on the qualitative field distribution around a ring (see Figure 20 on page 20). For example, with the arrangement shown in Figure 24, the field along the sensor Y direction is tangential and weaker, so the X-axis should be reduced (ETX = 1 and ETY = 0). If both ETX and ETY are set to 1, the current bias is reduced in both directions the same way (i.e. without side-shaft correction) (see Table 15).

Table 15: Trimming Direction Parameters

ETX	Enable Trimming of the X-Axis
0	Disabled
1	Enabled
ETY	**Enable Trimming of the Y-Axis**
0	Disabled
1	Enabled

Magnetic Field Thresholds

The magnetic flags (MGL and MGH) indicate that the magnetic field at the sensor position is out of the range defined by the lower (MGLT) and upper magnetic field thresholds (MGHT) (see Figure 25).

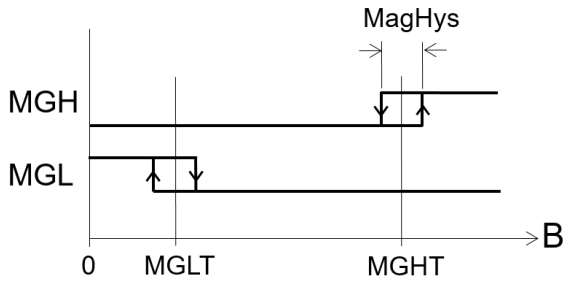


Figure 25: MGH and MGL Signals as a Function of the Field Strength

MagHys, the typical hysteresis on the MGH and MGL signals, is 6mT. The MGLT and MGHT thresholds are coded on 3 bits and stored in register 6 (see Table 16).

Table 16: Register 6

Register 6							
Bit[7]	**Bit[6]**	**Bit[5]**	**Bit[4]**	**Bit[3]**	**Bit[2]**	**Bit[1]**	**Bit[0]**
MGLT			MGHT			-	-

The 3-bit MGLT and MGHT values correspond to the magnetic field (see Table 17).

Table 17: MGLT and MGHT: Binary to mT Relationship

MGLT or MGHT (8)	Field Threshold in mT (7)	
	From Low to High Magnetic Field	From High to Low Magnetic Field
000	26	20
001	41	35
010	56	50
011	70	64
100	84	78
101	98	92
110	112	106
111	126	120

Notes:

7) Valid for V_{DD} = 3.3V. If different, then the field threshold is scaled by the factor V_{DD} / 3.3V.
8) MGLT can have a larger value than MGHT.

The MGL and MGH alarm flags are available to be read in register 27 (bit[6] and bit[7], respectively), and their logic state is also given at digital output pins 11 and 16.

To read the MGL and MGH flags via the SPI, send the 16-bit read command for register 27:

Command			*Reg. Address*					*MSB*							*LSB*
0	***1***	***0***	***1***	***1***	***0***	***1***	***1***	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*

The MAQ473 responds with the register 27 content in the next transmission:

Register 27 [7:0]				
MGH	**MGL**	**MIR[3:0]**	x	x

The MGL and MGH flags' logic state has no effect on the angle output.

Filter Window (FW)

The filter window (FW) affects the effective resolution (defined as the ±3σ noise interval) and the output bandwidth, which is characterized by f_{CUTOFF}.

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Table 18 gives the resulting resolution and bandwidth for each window.

Table 18: FW

FW[7:0]	τ (µs)	Effective Resolution at 45mT (Bits)	f_{CUTOFF} (Hz)	Start-Up Time (ms)
51	64	9.5	6000	0.5
68	128	10	3000	1.1
85	256	10.5	1500	2.5
102	512	11	740	5.5
119 (default)	1024	11.5	370	12
136	2048	12	185	26
153	4096	12.5	93	57
170	8192	13	46	123
187	16384	13.5	23	264

The time constant (τ) is the parameter entered in the transfer function (1). This allows the user to accurately model the system and analyze the stability of a control loop.

ABZ Incremental Encoder Output

The MAQ473 ABZ output emulates a 12-bit incremental encoder (such as an optical encoder), providing logic pulses in quadrature (see Figure 26). Compared to signal A, signal B is shifted by a quarter of the pulse period. During one revolution, signal A pulses *n* times, where *n* is programmable from 1 to 1024 pulses per revolution. The number of pulses per channel per revolution is programmed by setting parameter PPT, which consists of 10 bits split between registers 0x4 and 0x5 (see Table 8 on page 18). The factory default value is 1023. Table 19 describes how to program PPT[9:0] to set the required resolution.

Table 19: PPT

PPT[9:0]	Pulses per Revolution	Edges per Revolution
0000000000	1 (min)	4 (min)
0000000001	2	8
0000000010	3	12
0000000011	4	16
…	…	…
1111111100	1021	4084
1111111101	1022	4088
1111111110	1023	4092
1111111111	1024 (max)	4096 (max)

For example, to set 120 pulses per revolution (i.e. 480 edges), set PPT to 120 - 1 = 119 (binary: 0001110111). Table 20 shows how to set registers 4 and 5.

Table 20: Example PPT Setting for 120 Pulses

	Bit[7]	Bit[6]	Bit[5]	Bit[4]	Bit[3]	Bit[2]	Bit[1]	Bit[0]
R4	1	1	0	0	0	0	0	0
R5	0	0	0	1	1	1	0	1

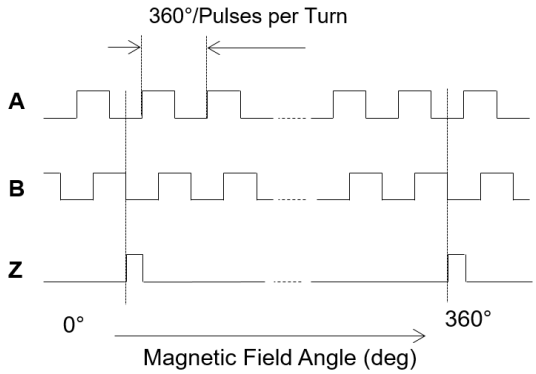


Figure 26: ABZ Output Timing

Signal Z (zero or index) rises only once per turn at the zero-angle position.

The position and length of the Z pulse is programmable via bits ILIP[3:0] in register 0x4 (see Figure 27).

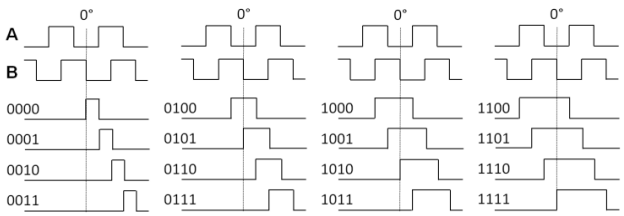


Figure 27: ILIP Parameter Effect on Index Shape

By default, the ILIP parameter is 0000. The index rising edge is aligned with the channel B falling edge. The index length is half of the A or B pulse length, depending on the user's selection.

ABZ Hysteresis

The hysteresis is set by the parameter HYS (see Table 21 on page 24). To avoid spurious transitions (see Figure 28 on page 24), it is recommended that the hysteresis be 12 times greater than the output root mean square (RMS) noise (1σ). Table 22 on page 24 shows indications of the 1σ noise.

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Table 21: HYS

HYS[7:0]	Hysteresis (deg)
200	0.08
188	0.14
148	0.18
152	0.36
156 (default)	0.52
116	0.70
120	1.4
124	2.1
84	2.8

Table 22: RMS Noise

FW(7:0)	Effective Resolution at 45mT (Bits)	1σ Noise (deg)
51	9.5	0.08
68	10	0.06
85	10.5	0.04
102	11	0.03
119 (default)	11.5	0.02
136	12	0.015
153	12.5	0.01
170	13	0.007
187	13.5	0.005

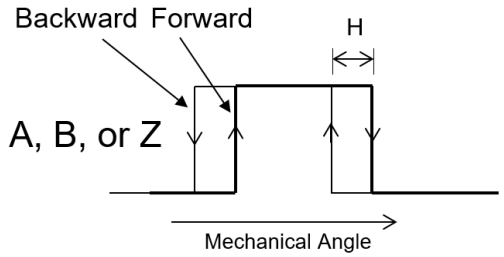


Figure 28: Hysteresis of the Incremental Output

ABZ Jitter

The ABZ state is updated at a frequency of 16MHz, enabling accurate operation up to a very high rpm (above 10^5rpm).

The jitter characterizes how far a particular ABZ edge can occur at an angular position different from the ideal position (see Figure 29).

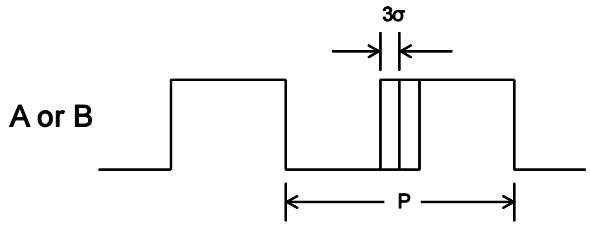


Figure 29: ABZ Jitter

The measurable jitter is composed by a systematic jitter (i.e. always the same deviation at a given angle, and given in the General Characteristics section on page 5) and a random jitter.

The random jitter reflects the sensor noise. Therefore, the edge distribution is the same as the SPI output noise. The random jitter is a function of the rotation speed. At lower speeds, the random jitter is less than the sensor noise.

This is a result of the fact that the probability of measuring an edge at a certain distance from the ideal position depends on the number of ABZ updates at this position.

PWM Absolute Output

This output provides a logic signal with a duty cycle proportional to the angle of the magnetic field. For the PWM frequency (f_{PWM}), see the General Characteristics section on page 5. The duty cycle is bound by a minimum value (1/514 of the period) and a maximum value (513/514 of the period), so it varies from 1/514 to 513/514 with a resolution of 14 bits (see Figure 30). The angle can be obtained by measuring the on time. Since the absolute f_{PWM} can vary from chip to chip or with the temperature, accurate angle detection requires measuring the duty cycle (i.e. measuring both the on time (t_{ON}) and the off time (t_{OFF})). The angle can be calculated with Equation (8):

$$\text{angle (in °)} = \frac{360}{512}\left(514\frac{t_{ON}}{t_{ON}+t_{OFF}} - 1\right) \quad (8)$$

Figure 30 shows one period of the PWM signal. The period (t) is 1 / f_{PWM}.

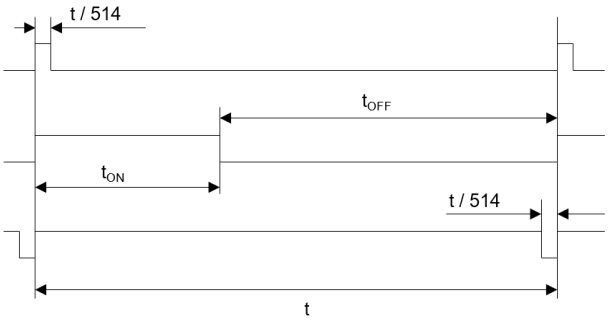


Figure 30: PWM Output Timing, Top Signal = 0°; Bottom Signal = Full Scale (i.e. 360° (1 - 1/16384))

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Diagnostic Features

The following features can be used to determine correct operation:

1. Parity bit on the angle (see the Parity Bit section on page 16).
2. Magnetic field in range via MIR[3:0] (see below).

Magnetic Field in Range

Bits MIR[3:0] in register 27 can be used to verify that the magnetic field is between the thresholds set by MGLT[2:0] and MGHT[2:0] in register 6. The value of MIR[3:0] is 0011 when the field is between these thresholds. This also indicates that the Hall sensor front end is functioning correctly and acquiring angle samples.

For example, assuming MGLT[2:0] is at its default value of 00 (15mT), and the MGHT[2:0] is at 111 (126mT), then if the field strength is between these values, the MIR[3:0] value is 0011.

Table 23 shows the MIR[3:0] values for the default threshold settings described above.

Table 23: MIR[3:0] Logic States

MIR[3:0]	Conditions MGLT[2:0] at default 15mT, MGHT[2:0] at default 126mT
0011	Field in range and Hall sensor array operational
1111	Field above MAGH and MAGL threshold (magnet too close to sensor)
0000	Field below MAGH and MAGL threshold (magnet too far away/missing)
0001	Invalid state: Hall array sensor functional error
0010	Invalid state: Hall array sensor functional error
0100	Invalid state: Hall array sensor functional error
1000	Invalid state: Hall array sensor functional error
1001	Invalid state: Hall array sensor functional error
1010	Invalid state: Hall array sensor functional error
1011	Invalid state: Hall array sensor functional error
1100	Invalid state: Hall array sensor functional error
1101	Invalid state: Hall array sensor functional error

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TYPICAL APPLICATION CIRCUITS

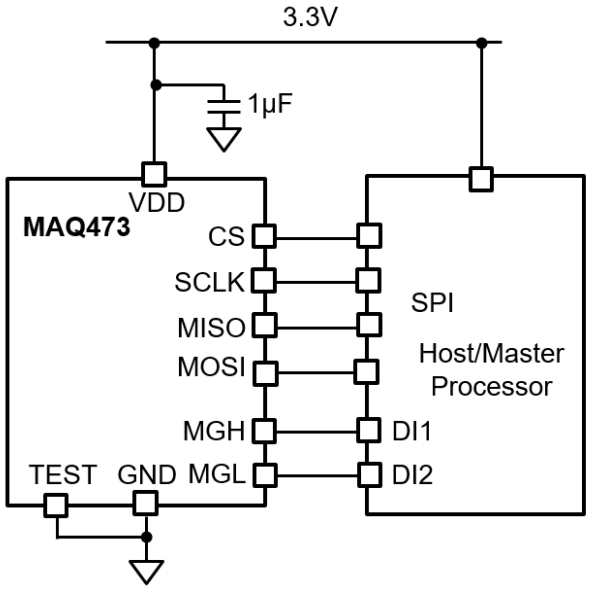


Figure 31: Typical Configurations Using SPI Interface and MGH/MGL Signals

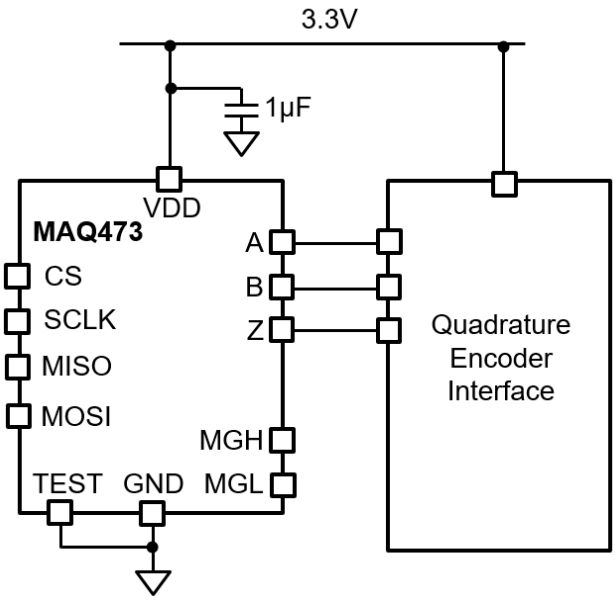
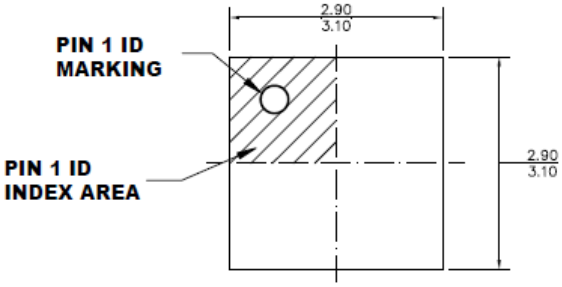


Figure 32: Typical Configuration Using ABZ Interface

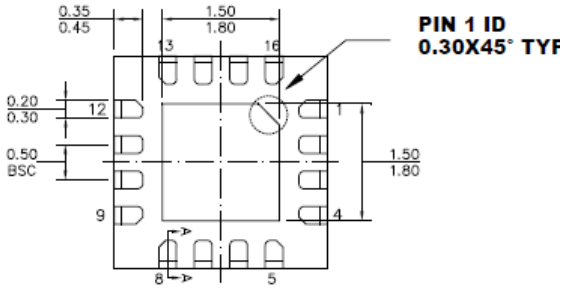
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PACKAGE INFORMATION

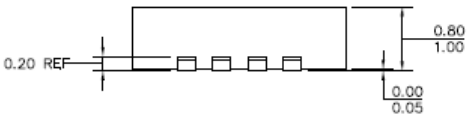
QFN-16 (3mmx3mm)



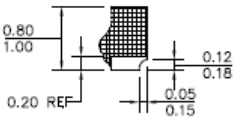
TOP VIEW



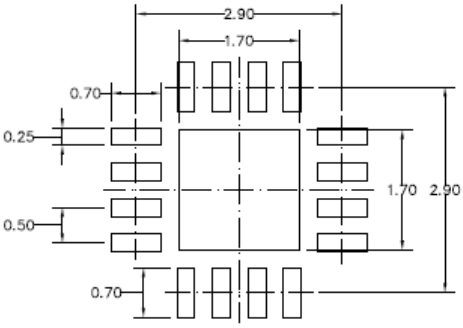
BOTTOM VIEW



SIDE VIEW



SECTION A-A



RECOMMENDED LAND PATTERN

NOTE:

1) THE LEAD SIDE IS WETTABLE.
2) ALL DIMENSIONS ARE IN MILLIMETERS.
3) EXPOSED PADDLE SIZE DOES NOT INCLUDE MOLD FLASH.
4) LEAD COPLANARITY SHALL BE 0.08 MILLIMETERS MAX.
5) JEDEC REFERENCE IS MO-220.
6) DRAWING IS NOT TO SCALE.

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APPENDIX A: DEFINITIONS

Effective Resolution (3σ noise level)

The smallest angle increment distinguishable from the noise. The resolution is measured by computing three times σ (the standard deviation in degrees) taken across 1,000 data points at a constant position. The resolution in bits is obtained with: $\log_2(360 / 6\sigma)$.

Refresh Rate

The rate at which new data points are stored in the output buffer.

ABZ Update Rate

The rate at which a new ABZ state is computed. The inverse of this rate is the minimum time between two ABZ edges.

Latency

The time elapsed between the instant when the data is ready to be read and the instant at which the shaft passes that position. The lag in degrees is lag = latency x *v*, where *v* is the angular velocity in deg/s.

Start-Up Time

The time until the sensor delivers valid data beginning at start-up.

Integral Nonlinearity (INL)

Maximum deviation between the average sensor output (at a fixed position) and the true mechanical angle (see Figure A1).

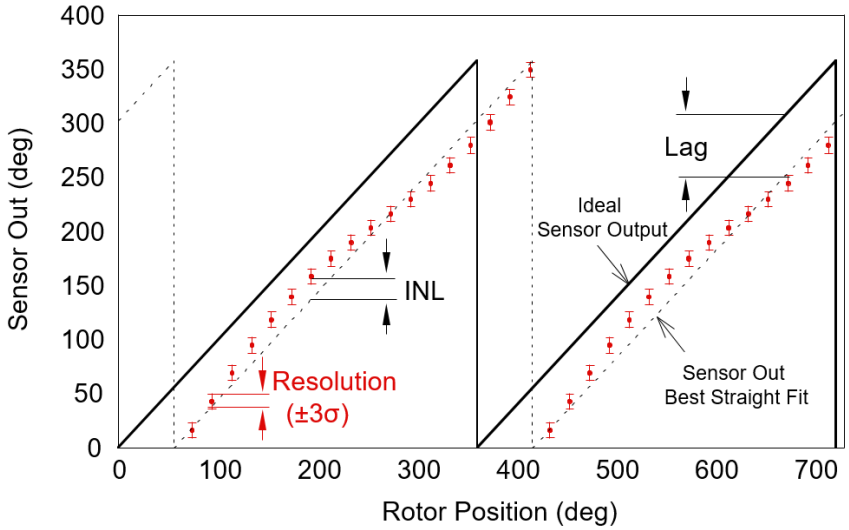


Figure A1: Resolution, INL, Lag

INL can be obtained from the error curve err(a) = out(a) - a, where out(a) is the average across 1,000 sensor outputs and *a* is the mechanical angle indicated by a high-precision encoder (<0.001°). INL is then calculated with Equation (A1):

$$INL = \frac{\max(err(a)) - \min(err(a))}{2} \quad (A1)$$

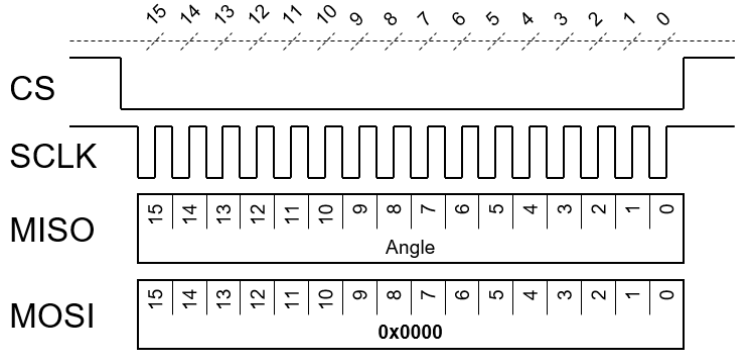
Drift

The angle variation rate when one parameter is changed (e.g. temperature, V_{DD}) but all others, including the shaft angle, remain constant.

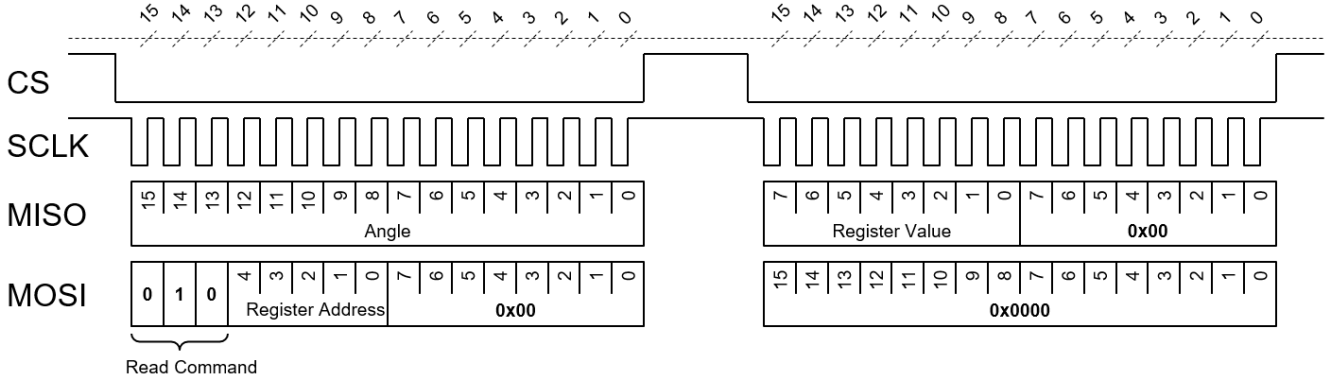
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APPENDIX B: SPI COMMUNICATION CHEATSHEET

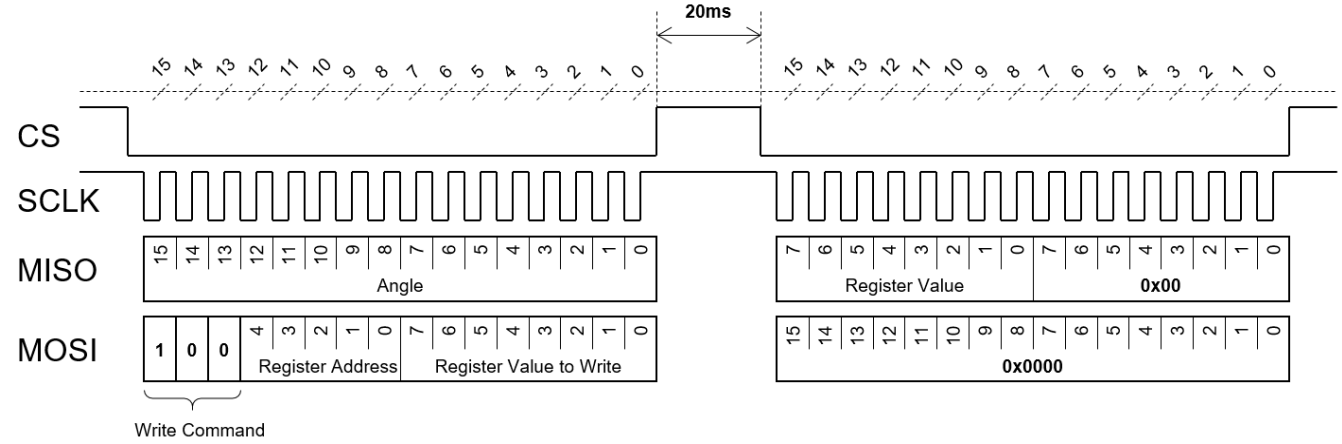
Read Angle



Read Register

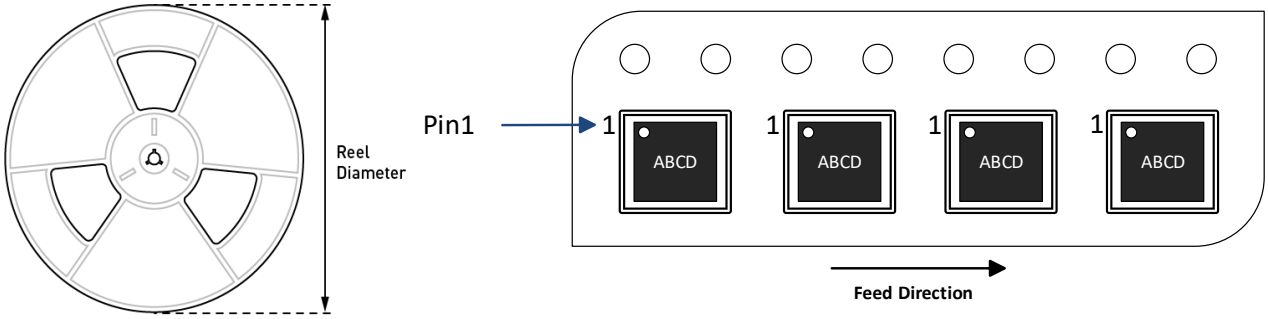


Write Register



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CARRIER INFORMATION



Part Number	Package Description	Quantity/ Reel	Quantity/ Tube	Quantity/ Tray	Reel Diameter	Carrier Tape Width	Carrier Tape Pitch
MAQ473GQE-AEC1-Z	QFN-16 (3mmx3mm)	5000	N/A	N/A	N/A	13in	12mm

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REVISION HISTORY

Revision #	Revision Date	Description	Pages Updated
1.0	5/12/2021	Initial Release	-

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