Design Guide: TIDA-010947

High Resolution Low Latency Compact Absolute Angle Encoder Reference Design With AMR Sensor

Description

This reference design demonstrates a small form factor absolute single-turn magnetic rotary angle encoder circuit design using a high-precision analog AMR 360° angle sensor with sine and cosine differential ratio metric analog outputs and integrated quadrant detection using Hall sensors. The Cortex M0 MCU includes 4MSPS dual sampling 12-bit ADCs and up to 14-bit effective resolution at 250-ksps with hardware averaging for low noise and low latency absolute angle calculation and a 4Mbaud UART for high-speed data transmission. The absolute encoder requires a 5V input supply voltage with ±10% tolerance and offers a bidirectional communication interface using a half-duplex RS-485 transceiver.

Resources

TIDA-010947	Design Folder
TMAG6180	Product Folder
MSPM0G3507	Product Folder
THVD1454	Product Folder
REF3533, TPS7A0533	Product Folder

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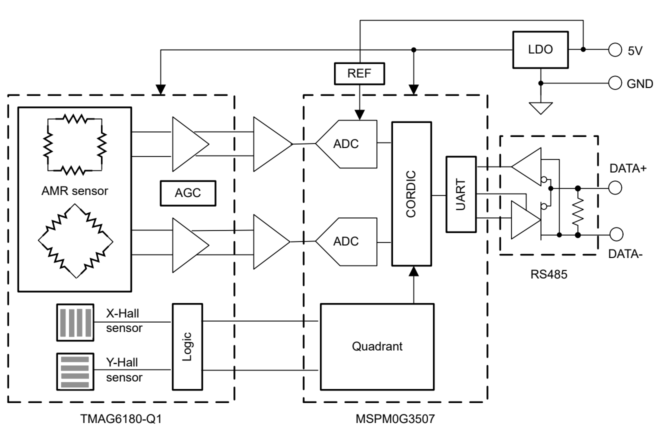
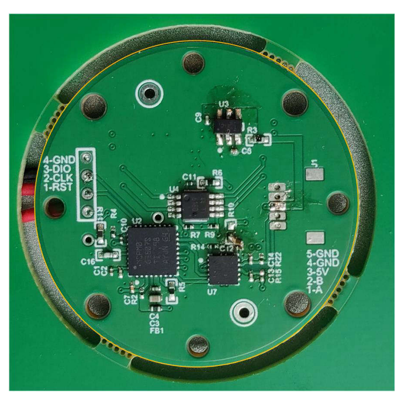
Features

- Low noise absolute rotary angle better than 15 ENOB, angle accuracy error less than 0.05° at 25°C and low latency 16us
- Small IC packages enable a compact circular PCB with a diameter of 30mm
- AMR sensor and integrated Hall sensors for quadrant detection enable full 360° measurements and reduce BOM count
- Wide operating magnetic field range 20mT to 1T enables flexible mechanical placement
- MCU with integrated dual 12-bit ADC and up to 128-times oversampling and math accelerator help improve efficiency and reduce system cost
- RS485 transceiver with integrated 120Ω switchable termination in a VSON-10 package help reduce BOM and space

Applications

- Servo Drive Position Sensor
- Position Sensor
- Traction Inverter Position Sensor





1 System Description

Single or multi-turn absolute rotary angle encoders are used in many applications such as servo drives and robotics, where an absolute mechanical angle position is required. Absolute encoders typically offer a serial unidirectional or bidirectional half-duplex or full-duplex RS485 interface with vendor specific or open encoder protocols.

This reference design demonstrates a small form-factor absolute single-turn magnetic rotary angle encoder circuit design using on-axis sensing, as shown in Figure 1-1. A circular disc magnet is mounted to the end of the rotating shaft of the encoder. A static PCB with the TMAG6180-Q1 high-precision analog AMR 360° angle sensor is mounted on-axis with configurable air gap from the top of the AMR sensor package to the circular disc magnet. The effective air gap includes the location of the AMR and Hall sensor inside the IC package. The integrated two independent Hall sensor outputs at X and Y axes are used to extend the angle range of the sensor to 360° mechanically.

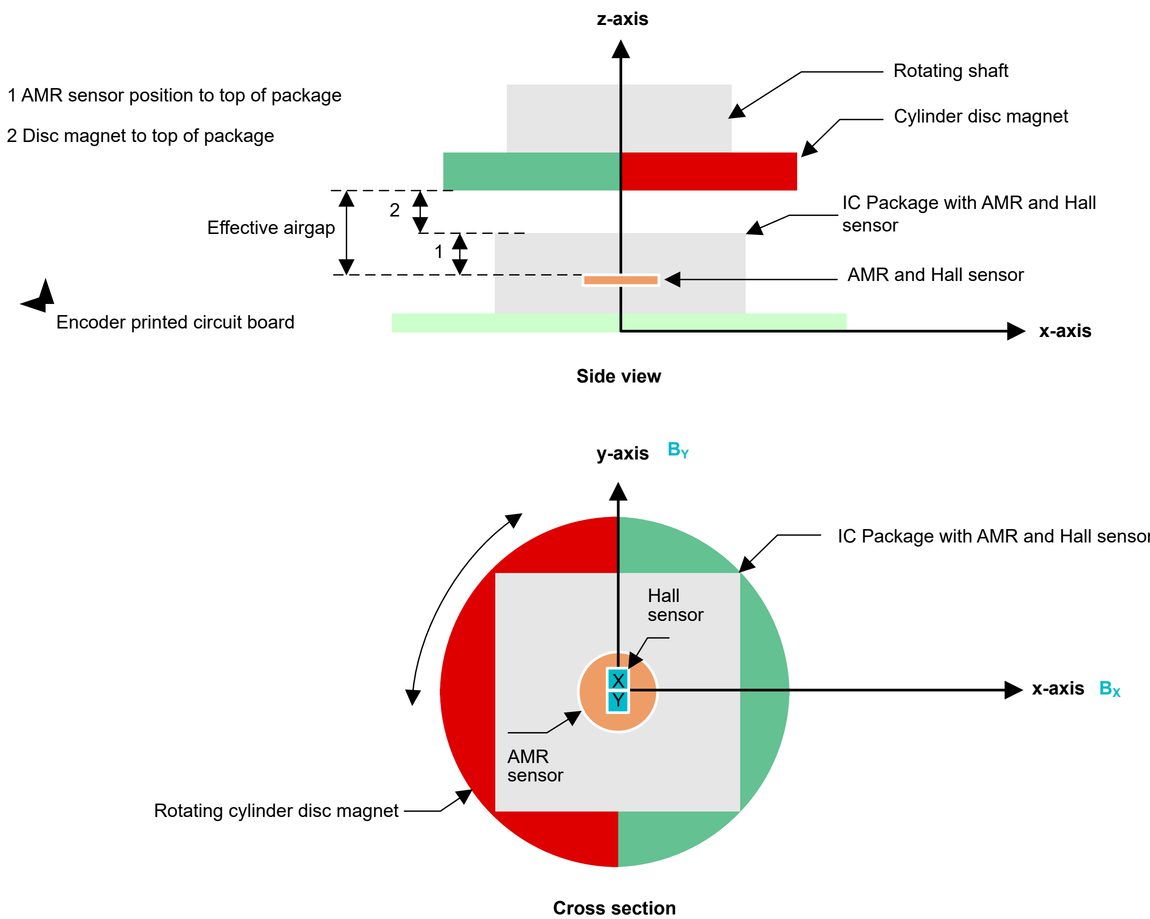


Figure 1-1. On-Axis Magnetic Angle Sensing Principle

The TMAG6180-Q1 features integrated signal conditioning amplifiers and provides differential sine and cosine analog outputs related to the direction of the applied in-plane magnetic field.

A Cortex M0 MCU MSPM0G3507 with 4MSPS dual sampling 12-bit ADC with up to 128-times hardware integrated averaging enables low noise and low latency absolute angle calculation and a 4-Mbaud UART for high-speed rotary angle data transmission. The absolute encoder circuit design offers a bidirectional interface using a half-duplex RS-485 transceiver with integrated 120Ω switchable termination in a small 10-VSON package. A 5V supply with ±10% tolerance is required to power the absolute encoder circuit.

1.1 Key System Specifications

The key specifications of the TIDA-010947 high resolution low latency compact absolute angle encoder reference design with AMR sensor is provided in Table 1-1.

Table 1-1. Key Design Specifications

Parameter	Value (Typical)	Comment
Function	Single-turn magnetic absolute angle encoder	
Sensor type	TMAG6180-Q1 high-precision analog AMR 360° angle sensor	On-axis sensing
Magnet	13mm diameter, 1mm thick, Neodymium N52, Br = 1455	End of shaft mounted for on-axis sensing
Magnet to sensor placement	End of shaft	
Airgap	0.8mm	Configurable
Angle accuracy error at 25°C	≤ 0.05°	Offset and gain error calibrated at 25°C
Angle standard deviation	≤ 0.0033°	
Angle resolution (standard deviation)	15.4 effective number of bits (ENOB)	
Angle resolution (numerical)	32-bit (IQ21)	Custom specific on MSPM0G3507
Angle propagation delay at 64-times oversampling (latency)	16 us	Time from effective sampling point of magnetic field strength in x- and y-direction to angle calculated
Effective angle sample rate	32kHz	
Operating speed	≤ 100000 rpm	Not tested
A/D converter	Dual 12-bit ADCs with 64-times hardware averaging	Integrated to MSPM0G3507, ADC oversampling configurable up to 128-times
A/D converter oversampling rate	2.85 MSPS (250ns sample time, 100ns conversion time)	Configurable sample time, 150ns minimum
Connector	5-pin, 1mm connector	Refer to **table 4-1**
Interface	RS485	THVD1454 half-duplex transceiver with Integrated 120Ω switchable termination
Supply voltage	5V ±10%	
Supply current consumption	54mA	Average current at 16kHz T-format command frequency
Operating temperature range	-40°C to 125°C	Reference design tested at 25°C ambient temperature
PCB diameter	30mm	
PCB layers	4	

2 System Overview

2.1 Block Diagram

The block diagram of this reference design is shown in Figure 2-1.

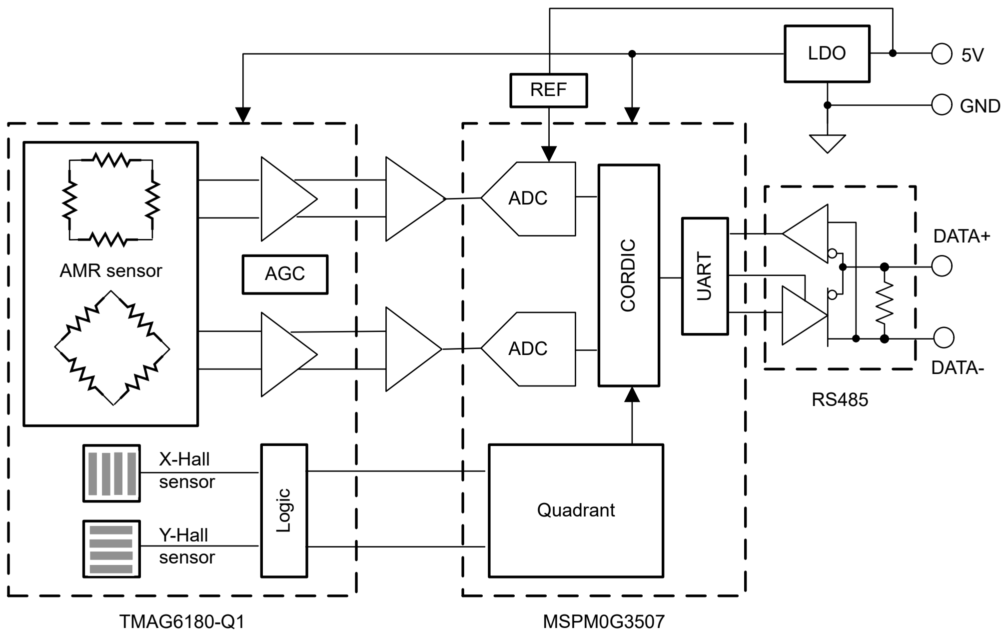


Figure 2-1. System Block Diagram

2.2 Design Considerations

Magnetic encoders are popular in harsh industrial applications due to the magnetic encoders wide operating temperature range up to 125°C ambient and robustness against shock and vibration.

The magnetic sensor can be a Hall-effect sensor or a magneto resistive sensor, such as an Anisotropic Magneto Resistive (AMR) sensor, which typically have a lower noise than a Hall-effect sensor. However, magneto resistive sensors measure the magnitude of the magnetic field, but cannot sense the direction. Therefor additional sensors, such as digital Hall switches are required to extend the measurement range to 360°.

For motor integrated encoder applications with the magnet mounted at the end of shaft, on-axis sensing with two ARM sensors which are 45° rotated against each other are well designed.

The electrical signal chain offset and gain mismatch as well as sample rate, speed and resolution of the analog to digital converter impact the accuracy of the measured absolute angle and components with very low temperature drift help reduce the angle error. Decoding of the angle from the sine and cosine sensor signals require math functions such as division, multiply-and -accumulate and arc tangent.

Small footprint circuits with high integration and low power consumption are critical to design smallest form factor circular PCB of less than 30mm diameter. Since the encoder can be motor integrated, ambient operating temperatures at least up to 125°C are typically required.

The absolute encoder RS485 communication interface need to be designed for high EMC immunity to minimize bit errors during the data transmission.

2.3 Highlighted Products

2.3.1 TMAG6180-Q1

The TMAG6180-Q1 is a high-precision angle sensor based on Anisotropic Magneto Resistive (AMR) technology. The device features integrated signal conditioning amplifiers and provides differential sine and cosine analog outputs related to the direction of the applied in-plane magnetic field. This device also features two independent Hall sensor outputs at X and Y axes that can be used to extend the angle range of the sensor to 360°. The key features with this design are:

- High-speed AMR angle sensor with ultra-low latency < 2us
- Low angle drift eliminates the need for calibration across temperatures
- Sine and cosine differential ratio metric analog outputs supports differential-ended or single-ended applications
- Wide operating magnetic field range: 20mT to 1T
- Integrated Quadrant Detection using Hall sensors
- Temperature range –40°C to 150°C

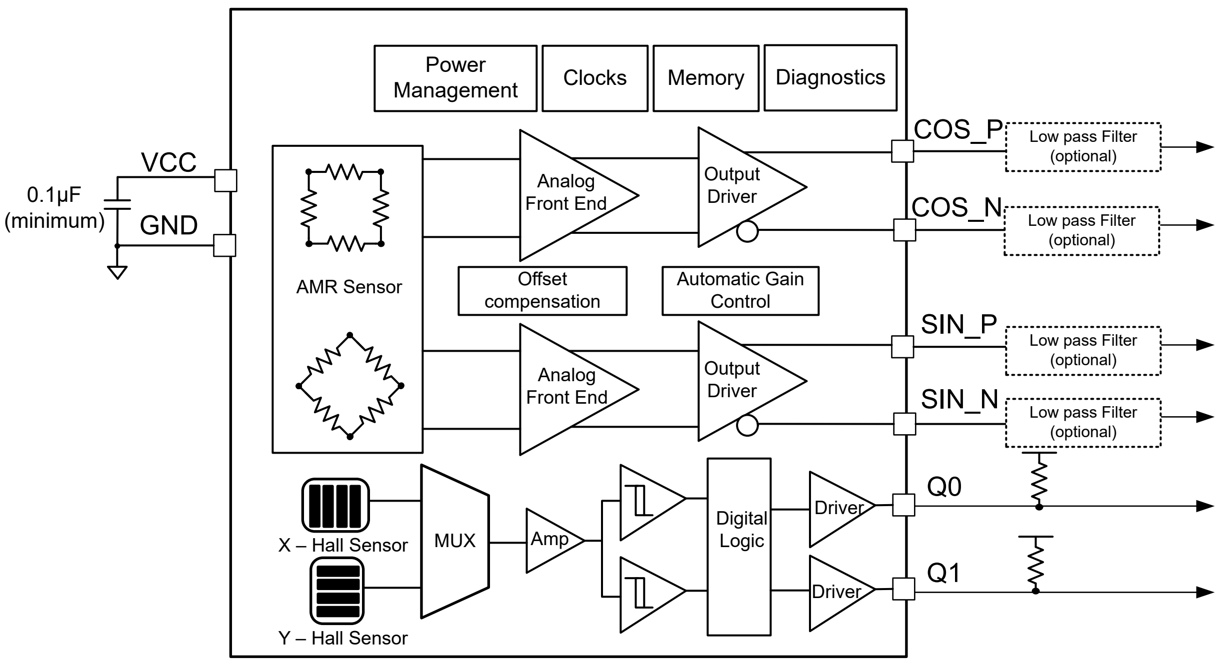


Figure 2-2. TMAG6180 Functional Block Diagram

2.3.2 MSPM0G3507

The MSPM0G350x microcontrollers (MCU) are part of the MSP highly integrated, ultra-low-power 32-bit MCU family based on the enhanced Arm™ Cortex®-M0+ 32-bit core platform operating at up to 80MHz frequency. These cost-optimized MCU offer high-performance analog peripheral integration, support extended temperature ranges from -40°C to 125°C, and operate with supply voltages ranging from 1.62V to 3.6V. The MSPM0G350x MCU key features with this design include:

- Two simultaneous sampling 12-bit 4-Msps analog-to-digital converters (ADC) with up to 17 external channels
- 14-bit effective resolution at 250-ksps with hardware averaging
- Optimized low-power modes
  - RUN: 96µA/MHz (CoreMark)
  - STANDBY: 1.5µA with RTC and SRAM retention
- Math accelerator supports DIV, SQRT, MAC, and TRIG computations

2.3.3 THVD1454

The THVD1454 is a half-duplex RS-485 transceiver for industrial applications. The device has features such as an on-chip, 120Ω termination resistor and driver output slew rate control. The key features with this design are:

- Pin controlled on-chip 120Ω termination resistor between the bus pins
- Maximum Data rate configurable – SLR = High: 500kbps – SLR = Low or floating: 20Mbps
- Bus I/O protection
  - ±16kV HBM ESD
  - ±8kV IEC 61000-4-2 Contact discharge, ±15kV IEC 61000-4-2 Air gap discharge
  - ±4kV IEC 61000-4-4 Fast transient burst
  - ±16V bus fault protection (absolute max voltage on bus pins)
- Extended industrial temperature range: -40°C to 125°C

3 System Design Theory

3.1 Hardware Design

3.1.1 Angle Sensor Schematic Design

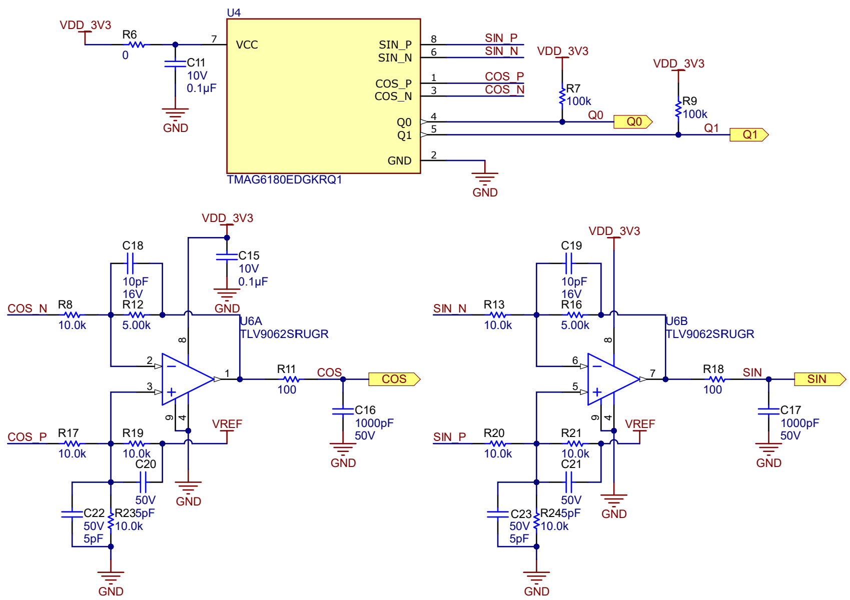


Figure 3-1. AMR Sensor TMAG6180 Schematic

A 100nF decoupling capacitor C11 is added close to the TMAG6180's VCC and GND pin. Q0 and Q1 are open-drain outputs, and 100k pull-up resistors R7 and R9 are connected to 3.3V power rail.

The TLV9062 is optional and used to convert the TMAG6180-Q1 differential analog outputs SIN_P, SIN_N and COS_P, COS_N to a single-ended signal to connect to the MSPM0G3507 ADC. There is the possibility to bypass TLV9062 by populating R8, R11, R12 , R13, R16, R18 as 0Ω resistor. To make sure the stable supply voltage at VCC, C15(100nF) is placed between VCC and GND.

The differential gain of TLV9062 can be calculated by Equation 1.

$$\frac{V_O}{V_{in}} = \frac{R_{12}}{R_8} = \frac{R_{19} \parallel R_{23}}{R_{17}} = \frac{1}{2} \quad (1)$$

Chose unit gain and let R8 be 10kΩ, so R17and R20 needs to be 10kΩ, R12 needs to be 5kΩ.

C18 is added to filter out high frequency noise. The bandwidth (BW) can be calculated by Equation 2.

$$BW = \frac{1}{2\pi C_{18} R_{12}} = \frac{1}{2\pi (C_{20} \parallel C_{22})(R_{19} \parallel R_{23})} \quad (2)$$

Chose 3MHz bandwidth, C18 can C19 needs to be 10pF. C20 approximately C23 needs to be half of C18, which is 5pF.

3.1.2 MSPM0G3507 Schematic Design

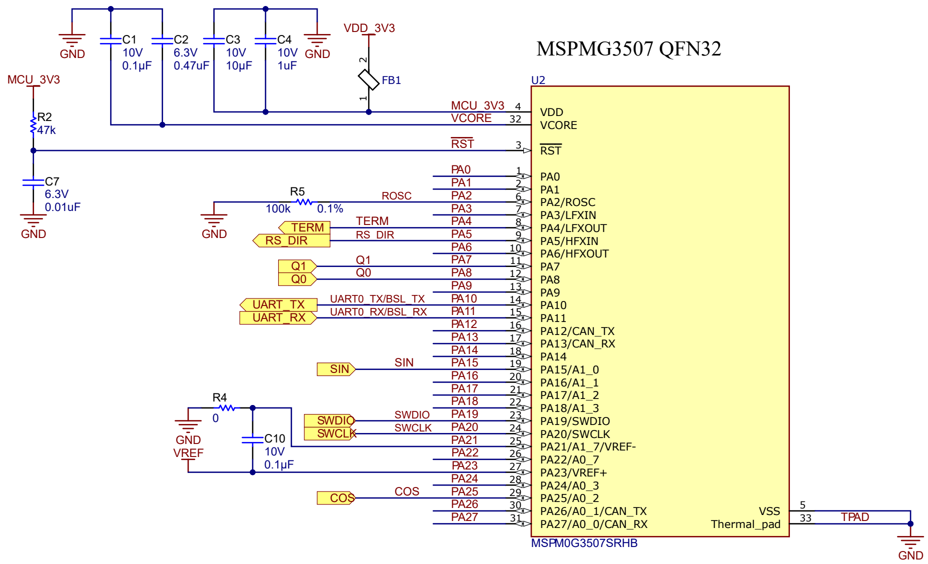


Figure 3-2. MSPM0G3507 Schematic

The ceramic decoupling capacitors C3 (10µF) and C4 (1µF) are placed across the VDD and VSS pins, and C1 (100nF), C2 (0.47uF) are placed across the VCORE and VSS pins. A ferrite bead FB1 is added between VDD and 3.3V power rail to avoid the high frequency digital current impacting the analog signal chain.

The nRST reset pin is pulled up to VDD with 47kΩ resistor R2 and 10nF pulldown capacitor C7. The SYSOSC frequency correction loop (FCL) circuit uses an external 100kΩ with 0.1% tolerance resistor R5 populated between the ROSC pin and VSS.

The MSPM0G3507 accepts an external reference to further improve the accuracy of the integrated ADC. In this design, an external 3.3V reference REF3533 is used and connected to the MSPM0G3507 VREF+ and VREF- pins. A 100nF decoupling capacitor (C10) is placed across VREF+ and VREF-.

3.1.3 RS485 Transceiver Schematic Design

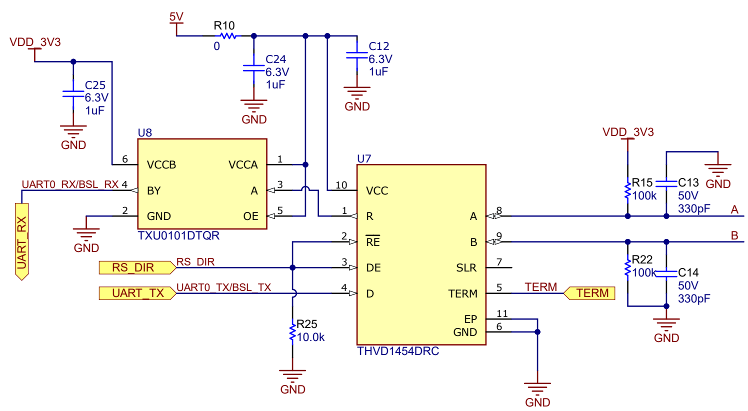


Figure 3-3. THVD1454 Schematic

To avoid the switching noise of RS485 transceiver influence the 3.3V power rail, which powers the TMAG6180, a separate 5V supply is used to supply the THVD1454. For reliable operation at all data rates and supply voltages, VCC supply needs to be decoupled with a 1uF ceramic capacitor (C12) located as close to the supply pin as possible. This reference design also uses a level shifter TXU0101 to convert the 5V signal on the THVD1454 R pin to a 3.3V signal to be compatible with MSPM0 GPIO input voltage range.

DE and /RE pins are direction control pins of THVD1454, since THVD1454 works on half-duplex mode. DE and /RE pins are connected together. The pulldown resistor R25 (10kΩ) is added to make sure THVD1454 is working on receive mode by default.

THVD1454 has integrated a 120Ω terminal resistor which is controlled by the TERM pin. The TERM pin is connected to MSPM0 GPIO PA4 to to enable the internal terminal resistor through MSPM0 software.

The 100kΩ pullup resistor R15 and pulldown resistor R22 are connected to A and B separately. These resistors limit the residual clamping current into the transceiver and prevent the transceiver from latching up.

3.1.4 Power Supply and Reference Voltage

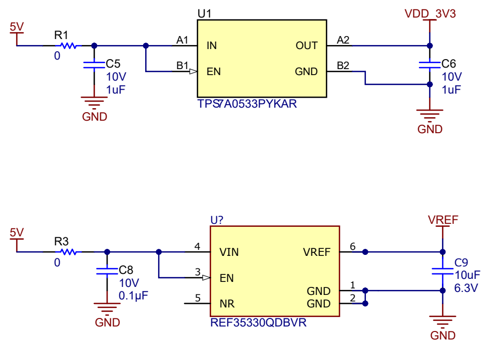


Figure 3-4. Power Supply Schematic

TPS7A0533 and REF3533 are used in this design to power the devices on the board. For TPS7A0533, the device accepts up to 5.5V input voltage and generates a 3.3V rail for TMAG6180, TLV9062, MSPM0G3507 and THVD1454 supply. Two parallel capacitors C5 (1µF) are used for noise decoupling, an output capacitor C6(10µF) is used for minimize the output voltage ripple.

For REF3533, the device is powered by an external 5V supply and generates precise 3.3V output as MSPM0 ADC's reference. Similarly with the TPS7A0533, C8 (100nF) is used for decoupling. C9(1uF) is used for minimize the output voltage ripple.

3.2 Software Design

To validate this reference design a TI internal test software has been developed with the MSPM0G3507 using the MSPM0 software development kit for M0 MCU.

3.2.1 Angle Calculation Timing

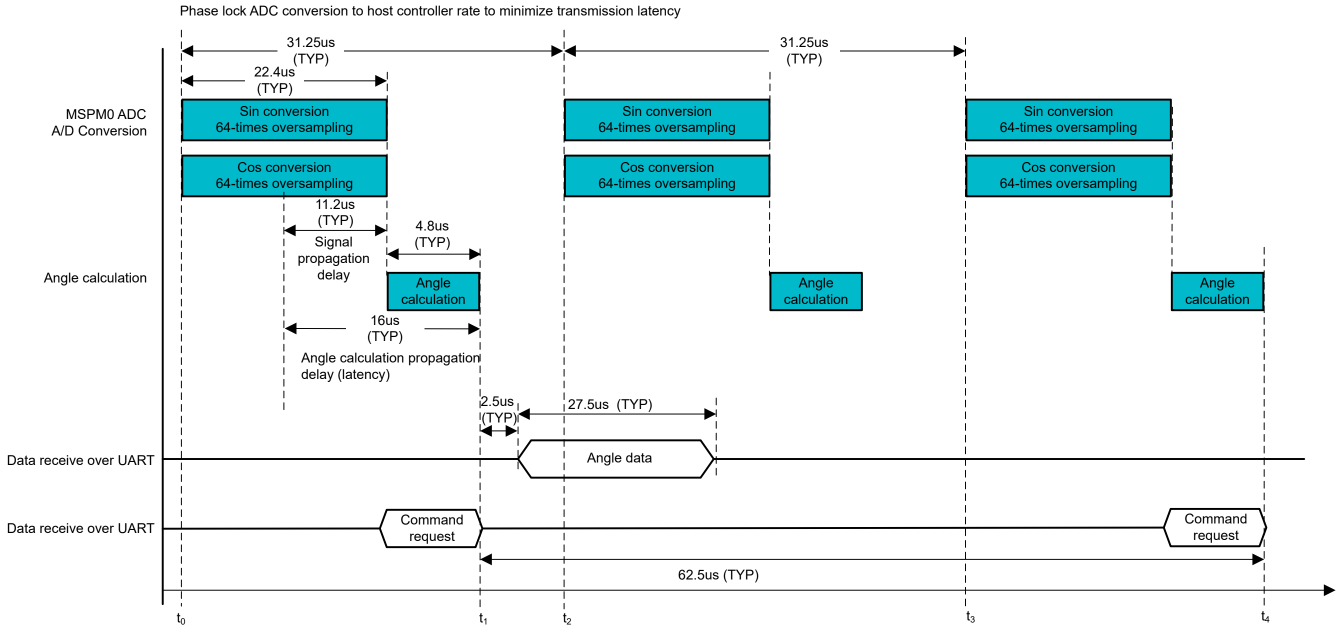


Figure 3-5. MSPM0G3507 Timing Diagram

In this reference design, the MSPM0G3507 integrated dual ADCs convert the TMAG6180's sine and cosine output signals. The MSPM0G3507 ADC are configured for 64-times hardware averaging and are simultaneous and periodically triggered by an internal 32kHz Timer0. The ADC end-of- conversion triggers an interrupt at which the two ADC conversion results and the status of the Hall latches Q0 and Q1 are read and the absolute angle is calculated.

When the host controller sends a command request to get position data, the controller triggers a UART interrupt in the MSPM0. Then the transmit data is stored to an array, and the DMA controller starts the UART transmission to the host controller.

The Timer0 interrupt is phase locked to encoder read command frequency from the host controller to minimize angle transmission latency and jitter.

3.2.2 Rotary Angle Calculation

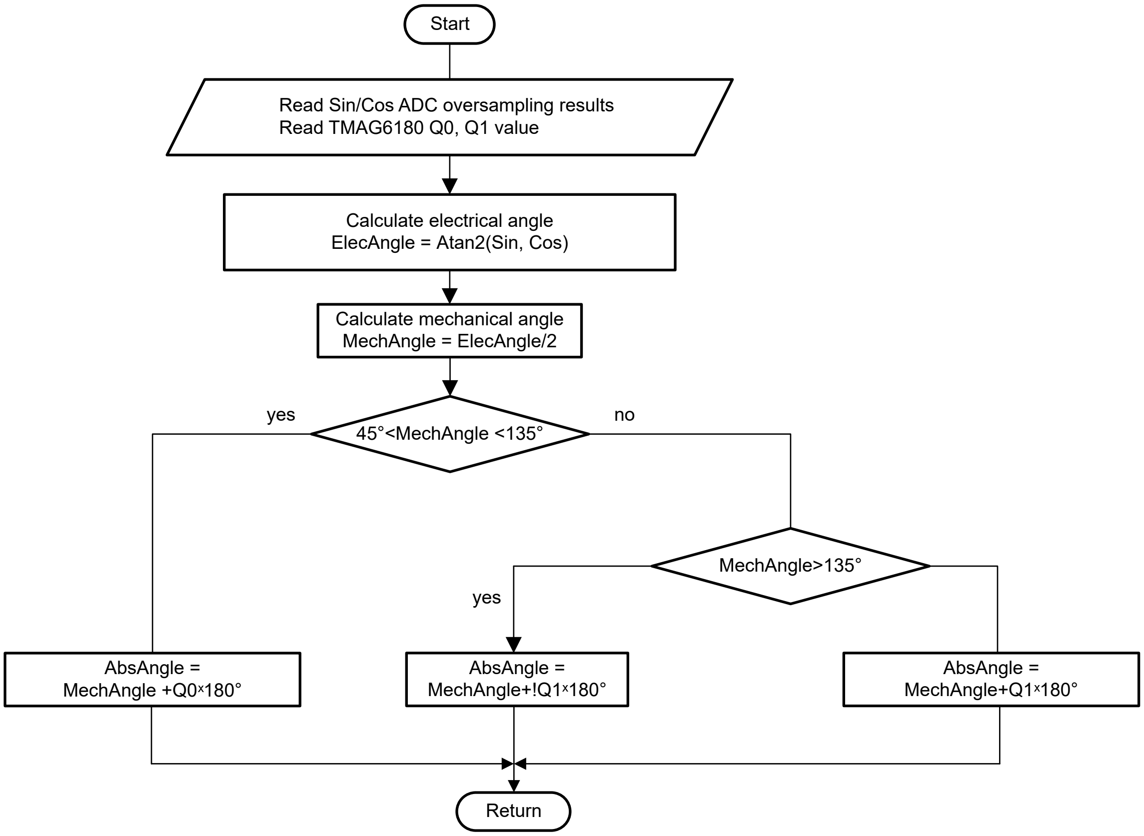


Figure 3-6. Angle Calculation Flow Chart

Since AMR sensors generate two sine and cosine periods over one mechanical revolution, additional sensing is required to distinguish between 0° to 180° and 180° to 360°. Therefore the TMAG6180 integrates two X,Y Hall switches, which help to extend the angle range from 180° to 360° using Q0 and Q1 outputs. The angle calculation flow chart is shown in Figure 3-6 and the example code in the following:

```
//-----------------------------------------------------------------------
//Angle calculation
//-----------------------------------------------------------------------
//comp0[0] = _IQ(0)
//comp0[1] = _IQ(1)
//comp1[0] = _IQ(1)
//comp1[1] = _IQ(0)
//-----------------------------------------------------------------------
    SinCosInput.SinCos.Sin = SinCosInput.SinCos.Sin - Adc16bitOffset;
    SinCosInput.SinCos.Cos = SinCosInput.SinCos.Cos - Adc16bitOffset;
//ATAN2 calculation
    DL_MathACL_startArcTan2Operation(MATHACL, &gAtanOpConfig, SinCosInput.SinCos.Sin,
SinCosInput.SinCos.Cos);
    DL_MathACL_waitForOperation(MATHACL);
    SinCosOutput.PhasePU = DL_MathACL_getResultOne(MATHACL);
    angle = _IQ(0.25) - (SinCosOutput.PhasePU>>1);
// Extend to 360 deg. 90 degree ~ 0.25, 45 degree ~ 0.125, 135 ~ 0.375
    if((angle <= _IQ(0.375)) && (angle>_IQ(0.125)))
        absangle=comp0[TMAG_Q0]+angle;
    else
    {
          if (angle>_IQ(0.375))
              absangle=comp1[TMAG_Q1]+angle;
          else
              absangle=_IQ(0.5)-comp1[TMAG_Q1]+angle;
    }
```

3.2.3 Rotary Angle Error Sources and Compensation

For accurate angle measurement, the center of the magnet need to be aligned to the center of the sensor with acceptable tolerances. Follow these steps to calibrate the sensor for best accuracy:

- Set the reference angle based on the magnet alignment to the sensor. This error can be saved in the microcontroller for run time absolute position calculation. This error is also known as angle offset in a system.
- Electrical offset calibration, see *Calibration of AMR Angle Sensors* for the offset calibration procedure. If the sensor cannot be rotated across the full range, then the electrical offsets cannot be calibrated.
- Amplitude mismatch calibration, see *Calibration of AMR Angle Sensors* for the amplitude mismatch calibration procedure. If the sensor cannot be rotated across the full range, then the amplitude mismatch cannot be calibrated.

Further error sources include non-linearity of the sensor signal chain such as the 3rd harmonics, and a mechanical error through coupling a reference angle encoder to the shaft of the absolute magnetic encoder. Figure 3-7 through Figure 3-10 outline the error source and the impact to the angular error to understand and compensate these types of errors.

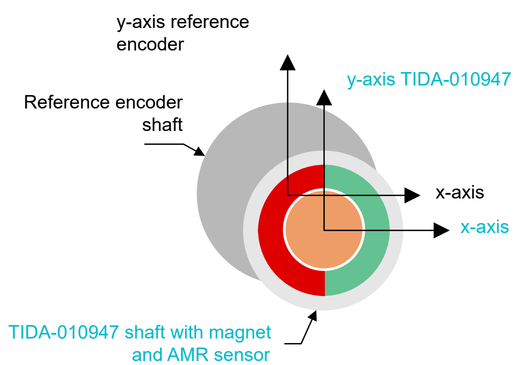


Figure 3-7. Shaft Coupling Mechanical Displacement

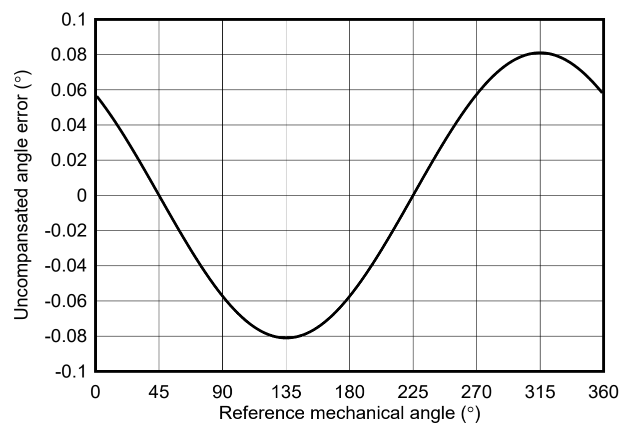


Figure 3-8. Angle Error Example due to Shaft Coupling Displacement

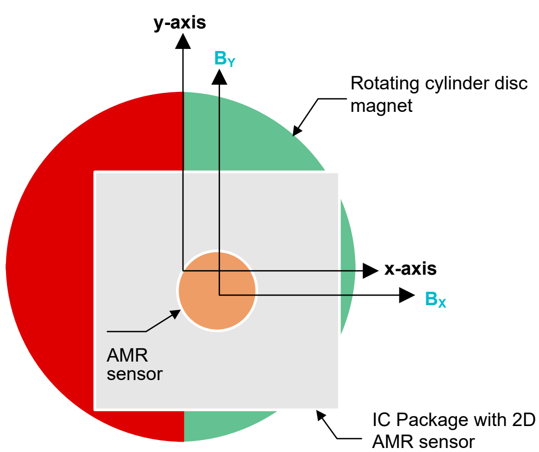


Figure 3-9. AMR Sensor Displacement

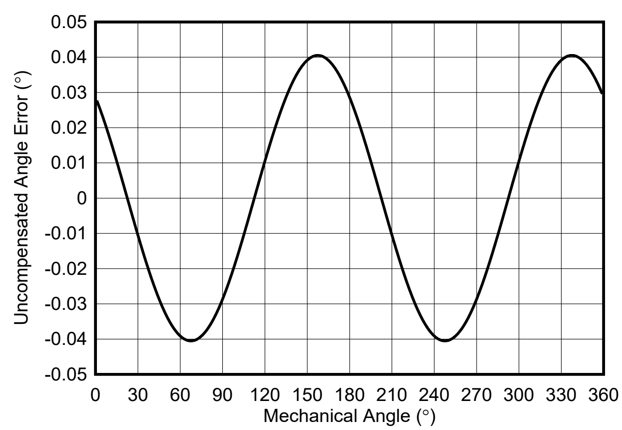


Figure 3-10. Angle Error Example due to AMR Sensor Displacement

Electrical offset, gain-mismatch and non linearity (3rd harmonics) of the sensor signal chain impact the angle error, examples are shown in Figure 3-11 to Figure 3-13.

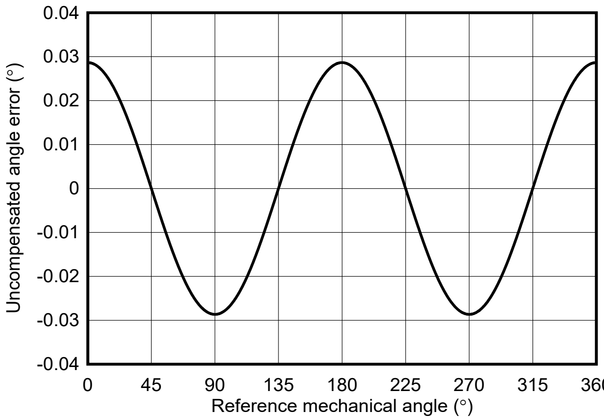


Figure 3-11. Angle Error Example due to AMR Sin/Cos Signal Chain Offset (0.1%)

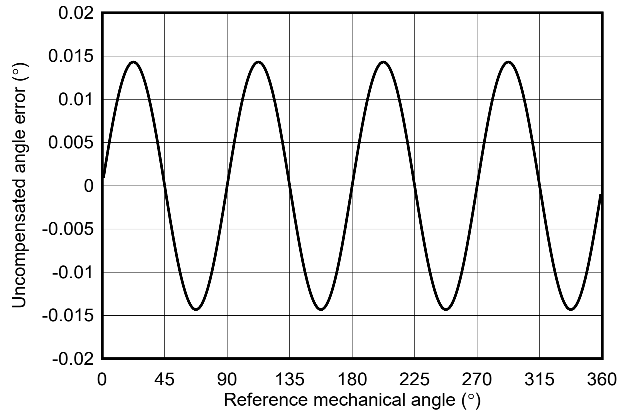


Figure 3-12. Angle Error Example due to AMR Sin/Cos Signal Gain Mismatch (0.1%)

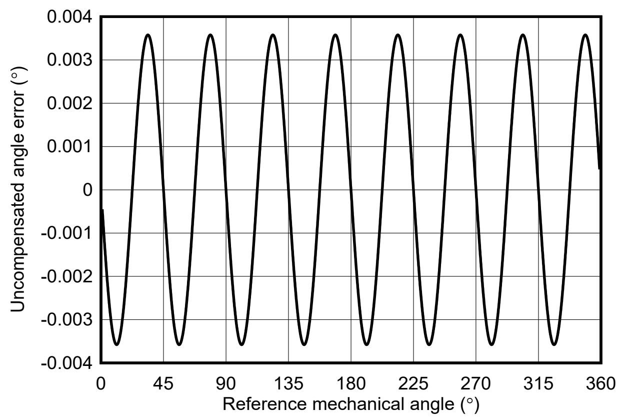


Figure 3-13. Angle Error Example due to AMR Sin/Cos Signal Chain Non-Linearity (-0.1%)

Table 3-1 summaries the impact on the angular error pattern.

Table 3-1. Errors Sources and Impact on Angle Error Harmonics

Error sources	Shaft coupling displacement	AMR sensor displacement	AMR sensor signal chain offset	AMR sensor signal chain gain mismatch	AMR sensor signal chain nonlinearity (3rd harmonic)
Angular error harmonic over 360 degree	1st	2nd	2nd	4th	8th

For more information on angle position calculation algorithms refer to *Achieving Highest System Angle Sensing Accuracy*, application note.

3.2.4 Encoder Communication Interface

This absolute encoder reference design communicates with the host controller through the RS485 interface to transmit the angle data. The communication runs at a 4M baud rate UART protocol. The host controller sends different T-format command request and the encoder responds with the corresponding field stipulated by the T-format protocol. Figure 3-14 shows an example communication. For more details on the T-format protocol, refer to *TAMAGAWA Encoder Catalog*.

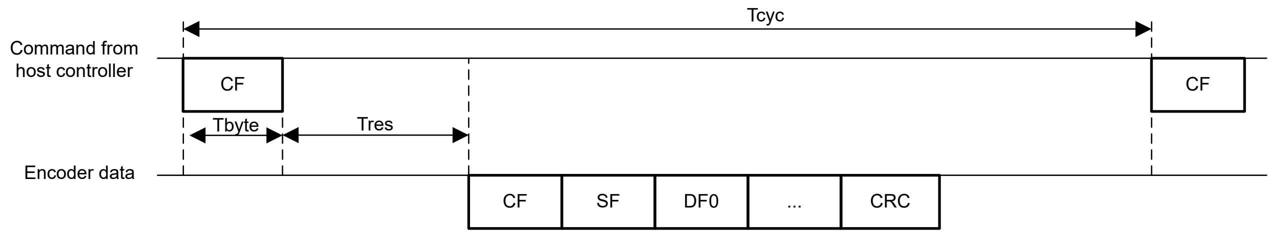


Figure 3-14. Command Request

The software is configured to respond to the ID3 command, which requires to return all of the encoder data, including command field, status field, single-turn data field, encoder ID, multi-turn field, alarm field, CRC field, total 11 bytes. The field format is listed in Table 3-2. Since the angle is calculated in IQ21 format in MCU, 3 bytes of data field are required to transmit the angle data.

Table 3-2. Field Format

	Bit1	Bit2	Bit3	Bit4	Bit5	Bit6	Bit7	Bit8	Bit9	Bit10
Content	Start bit, always 0	The content depends on the specific field. These 8 bits of data are included in the CRC calculation.								Stop bit, always 1

4 Hardware, Software, Testing Requirements, and Test Results

4.1 Hardware Requirements

4.1.1 PCB Overview

The PCB top and bottom view are shown in Figure 4-1 and Figure 4-2.

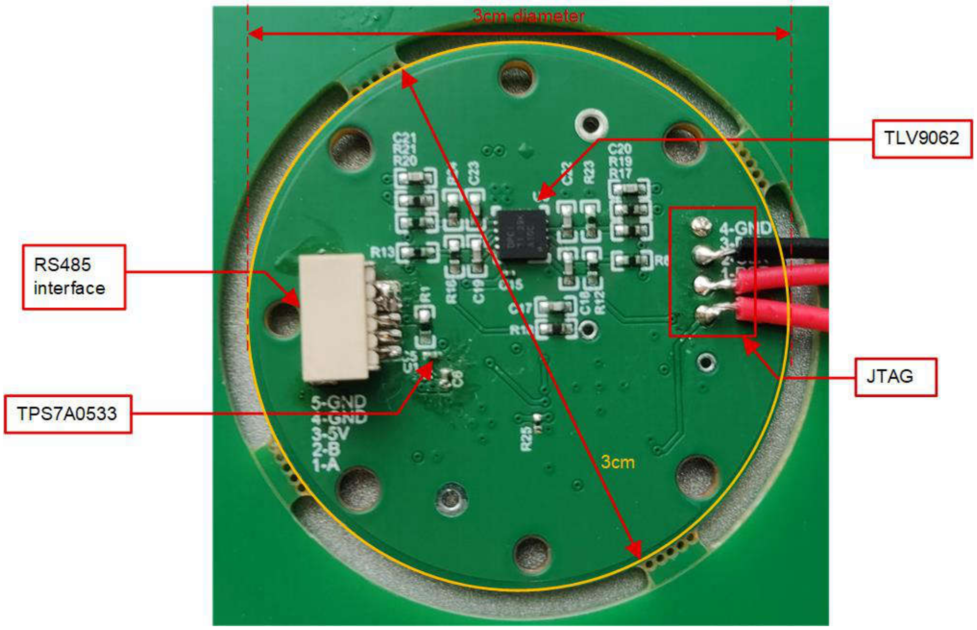


Figure 4-1. PCB Top View

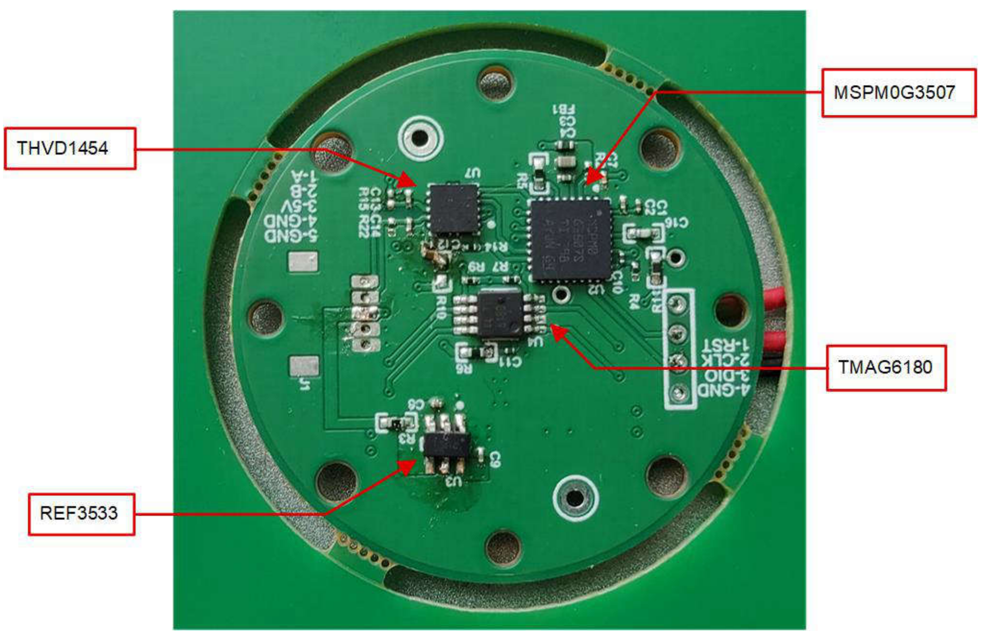


Figure 4-2. PCB Bottom View

4.1.2 Encoder and JTAG Interface

The TIDA-010947 interfaces are listed in Table 4-1 and Table 4-2. J1 is the RS485 data communication interface. The T-format is implemented over this interface to communicate with host MCU. J2 is the JTAG interface to MSPM0 MCU, which is used to download and debug the software.

Table 4-1. Encoder Interface

PIN	Signal	Comment
J1-1	DATA+	RS485 data+ signal
J1-2	DATA-	RS485 data- signal
J1-3	5V supply	External power supply
J1-4	GND	-
J1-5	GND	-

Table 4-2. JATG Interface

PIN	Signal	Comment
J2-1	RST	Input
J2-2	CLK	Input
J2-3	DIO	Input/Output
J2-4	GND	-

4.1.3 Software Requirements

To validate this reference design a TI internal test software has been developed with the MSPM0G3507 using the M0 software development kit for M0 MCU.

Table 4-3. Key Software Configuration

Sub-system	Parameter	Value
ADC0, ADC1	Sampling time	250ns
	Conversion time	100ns
	Hardware averaging	64-times
UART	Baud rate	4M
	Word length	8bit
Interrupt	ADC trigger frequency (Timer0)	32kHz
	Position calculation frequency	32kHz

4.2 Test Setup

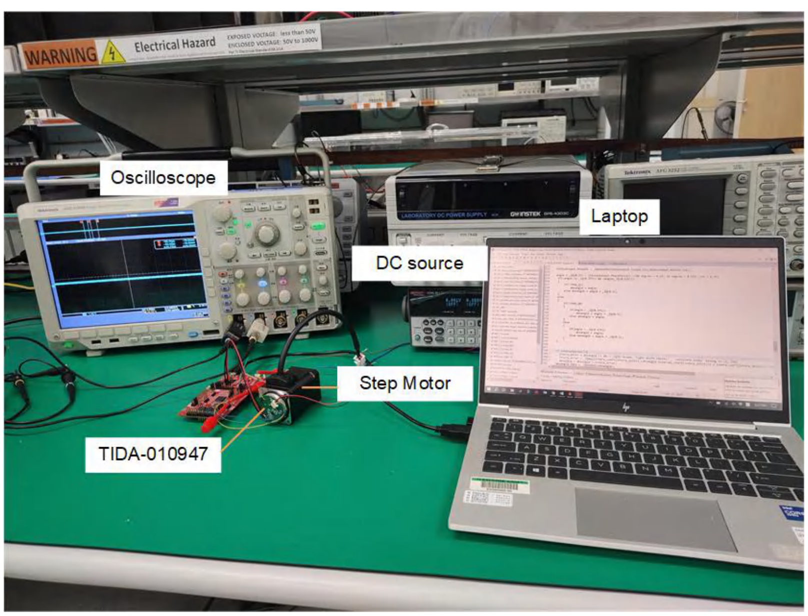


Figure 4-3. Test Setup

Figure 4-3 shows the static noise test setup in lab. The rotary angle accuracy test was done in external lab, there was no opportunity to take a picture there.

4.3 Test Results

4.3.1 AMR Sensor Sin and Cos Outputs Measurement

Figure 4-4 and Figure 4-5 show the AMR sensor sine and cosine signals converted to single-ended at the input of the MSPM0G3507 ADCs over half a mechanical revolution from 0 to 180 degree mechanically. The signals are biased to 1.65V and the peak to peak amplitude is around 2V. The maximum voltage is around 2.65V, the minimum voltage is around 0.65V. The full-scale input range of the MSPM0 internal ADC is 3.3V using external REF3533 reference. That means the AMR sensors use 62% of the full-scale range giving enough headroom for signal chain gain and offset changes.

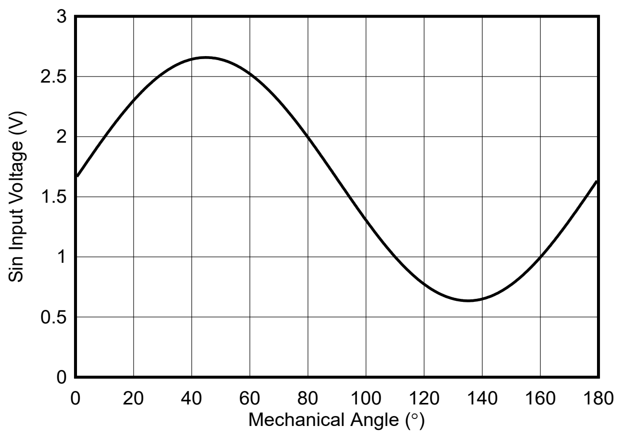


Figure 4-4. Single-Ended AMR Sensor Sine Waveform at the MSPM0 ADC1 Input

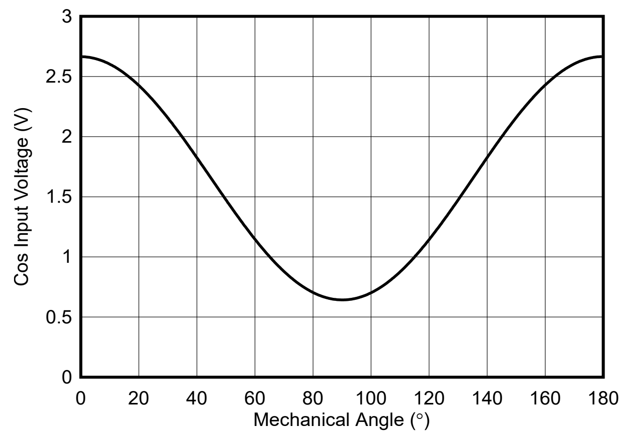


Figure 4-5. Single-Ended AMR Sensor Cosine Waveform at the MSPM0 ADC0 Input

To measure the signal to noise ratio and effective number of bits, 2000 consecutive of the sine and cosine signals where measured at a 32kHz sample rare and a fixed angle.

The following two figures show the offset corrected sine and cosine signals in the time domain over 62.5ms. The 1.65V bias voltage was subtracted from the corresponding A/D converted sine and cosine input signal. The peak to peak noise is within 0.6mV. Figure 4-6 and Figure 4-7 show the corresponding histogram of the sine and cosine signal.

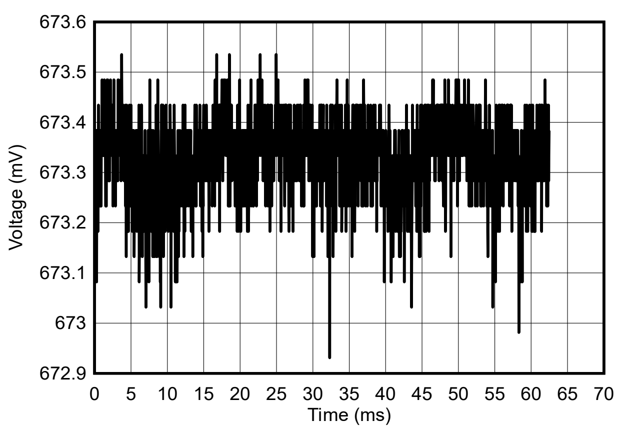


Figure 4-6. Sine Voltage Signal of AMR Sensor at Mechanical Angle of 67.48 deg With Bias Voltage Correction

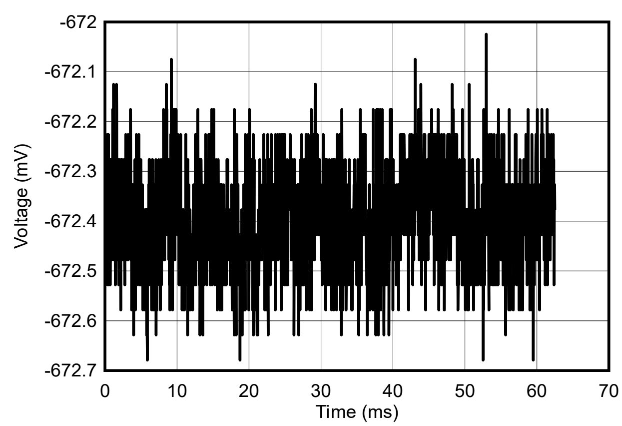


Figure 4-7. Cosine Voltage Signal of AMR Sensor at Mechanical Angle of 67.48 deg With Bias Voltage Correction

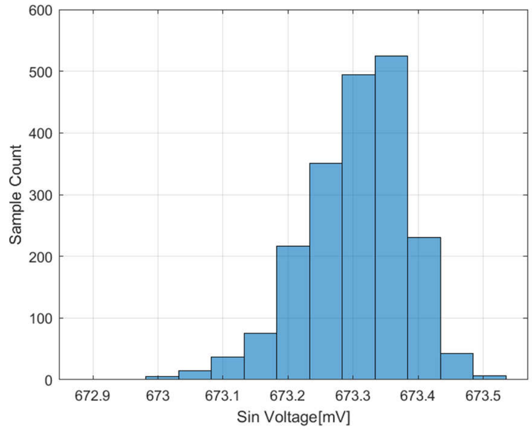


Figure 4-8. Histogram Sin Signal, 2000 Samples

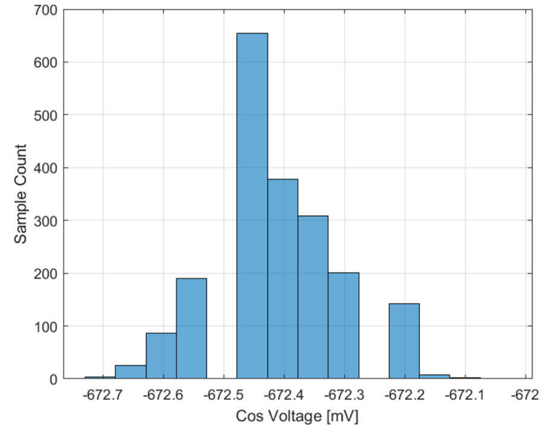


Figure 4-9. Histogram Cos Signal, 2000 Samples

The standard deviation, signal-to-noise ratio (SNR) and effective number of bits (ENOB) versus full-scale range are shown in Table 4-4. With the ADC in 64-times averaging mode the SIN signal's ENOB is 13.3 bit, the COS is 13 bit.

Table 4-4. Standard Deviation, SNR and ENOB versus TMAG6180 Full Scale Range

Parameter	X-axis	Y-axis	Comment
Standard deviation [mV]	0.082	0.101	RMS
Sin/Cos amplitude [V]	1	1	peak
SNR [dB]	81.7	80	dB
ENOB [bit]	13.3	13	Bit

4.3.2 Static Angle Noise Measurement

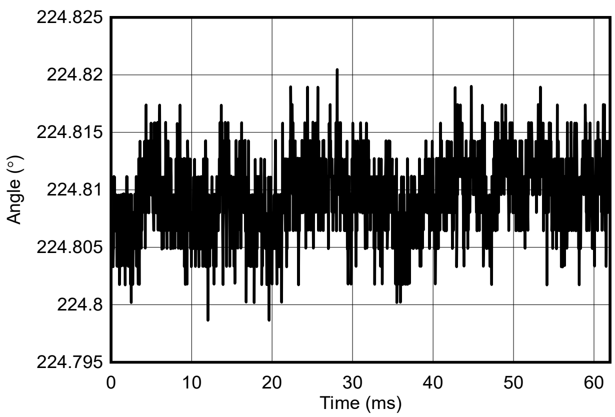


Figure 4-10. Static Angle at 224.8 deg Over 2000 Samples at 32kHz Sample Rate

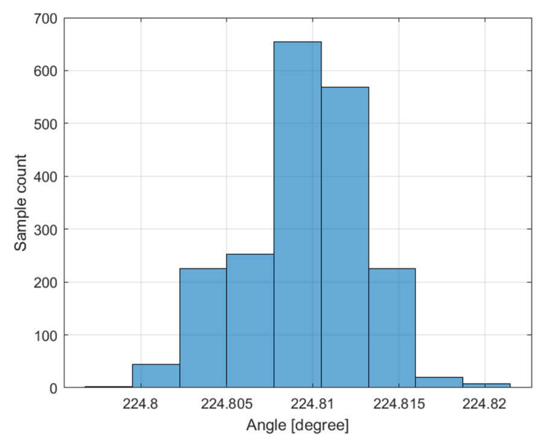


Figure 4-11. Histogram of Angle at 224.8 deg, 2000 Samples 1LSB at 17-bit bin Width

Keep the motor shaft at fixed 224.8° mechanical angle. MSPM0 calculates angle at 32kHz. Get 2000 angle samples, plot the time-domain figure and histogram in Figure 4-10 and Figure 4-11.

The corresponding standard deviation and ENOB versus full-scale position measurement range are shown in Table 4-5. The RMS of angle noise is 0.0033°, which means 94.7dB SNR versus 360° full scale range and 15.4 ENOB.

Table 4-5. Standard Deviation, SNR and ENOB at Static Angle 224.8° for TMAG6180

Parameter	Value	Comment
Standard deviation [°]	0.0033	RMS
Full-scale range [°]	0-360	
SNR [dB]	94.7	SNR=20×log10(±180 deg/STDEV)
ENOB [bit]	15.4	ENOB=(SNR-1.76)/6.02

Assuming uncorrelated noise, the theoretical total resolution of the absolute mechanical angle can increase by 2-bit versus the effective number of bits (ENOB) of the AMR sensors sine and cosine signal chain including the 12-bit ADC with 64-times oversampling. The theoretical resolution of the sin/cos interpolated angle over one electrical AMR sensor period equals the sine and cosine subsystem's ENOB + 1 bit. With this design there are two electrical periods per mechanical revolution, resulting in one additional bit.

Change the motor shaft angle with 22.5° interval. Get 2000 samples at each angle, the corresponding RMS and peak to peak value is listed in Table 4-6 and Table 4-7. The peak to peak static angle noise is around 0.02° and maximum value occurs at 225°.

Table 4-6. Static Angle Noise Over First Half Revolution (0 Approximately 180°)

Mechanical angle [°]	0	22.5	45	67.5	90	112.5	135	157.5
Standard deviation[°]	0.0025	0.0020	0.0028	0.0027	0.0026	0.0022	0.0028	0.0028
Peak to peak [°]	0.0185	0.0160	0.0227	0.0185	0.0184	0.0173	0.0182	0.0192

Table 4-7. Static Angle Noise Over Second Half Revolution (180° Approximately 360°)

Mechanical angle [°]	180	202.5	225	247.5	270	292.5	315	337.5
Standard deviation [°]	0.0029	0.0024	0.0031	0.0032	0.0026	0.0027	0.0019	0.0027
Peak to peak [°]	0.0182	0.0182	0.0225	0.0245	0.0184	0.0182	0.0151	0.0206

Figure 4-12 shows the peak to peak angle noise with black color with reference to the y-axis on the left over one mechanical revolution. The angle standard deviation is shown in red color with reference to x-axis in the right.

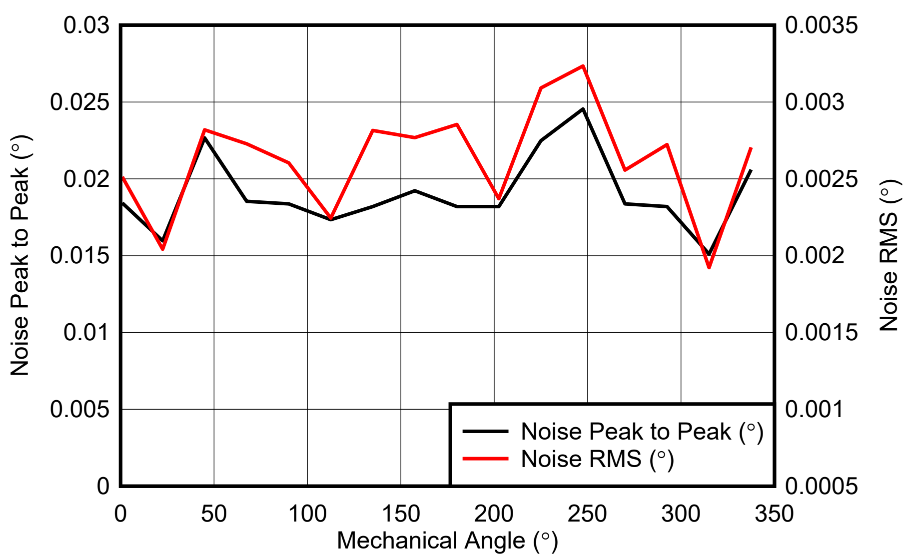


Figure 4-12. Static Angle Noise Over One Revolution

Table 4-8. Static Angle Noise vs Airgap

Mechanical angle [°]	0	45	90	135	180	225	270	315
Standard deviation at 0.8mm airgap [°]	0.0031	0.0025	0.0020	0.0029	0.0027	0.0033	0.0032	0.0031
Standard deviation at 2.3mm airgap [°]	0.0038	0.0024	0.0035	0.0031	0.0035	0.0034	0.0034	0.0033

Change the effective air gap to 2.3mm, measure the static angle noise at different mechanical angle, the comparison test results are shown in Table 4-8. At a larger airgap, the maximum noise RMS is 0.0038° while it's 0.0033° under 0.8mm airgap. A larger airgap can slightly increase the noise but the impact on the SNR and ENOB can be small.

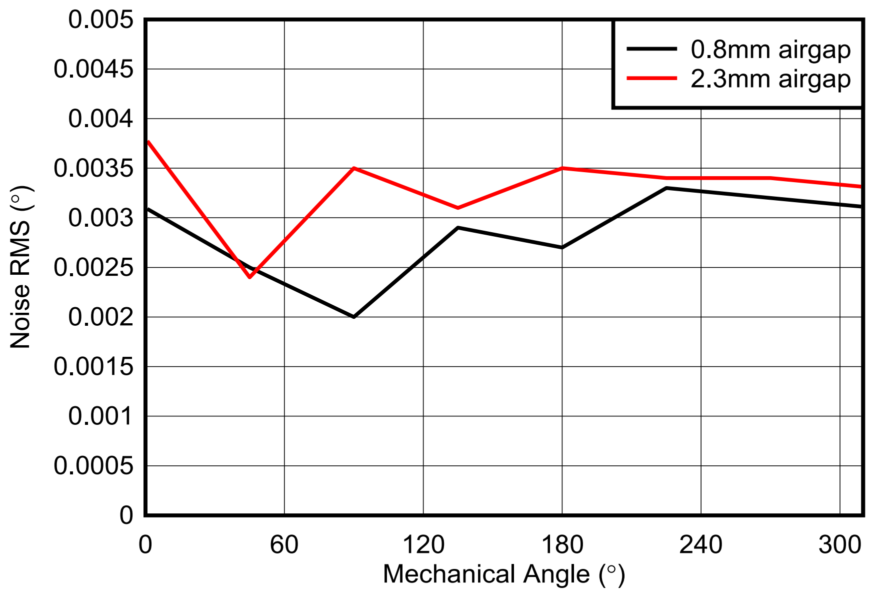


Figure 4-13. Static Angle Noise vs Airgap

4.3.3 Rotary Angle Accuracy Measurement

In this section, the angle accuracy when the motor is running on constant speed is tested. On test platform, the servo motor drives the tested motor at 30RPM. The host controller can send position data request command at 16kHz frequency and collect the reference encoder and TIDA-010947 position data. Compare the reference encoder and TIDA-010947 data to get the rotary angle accuracy.

For help simulating magnetic systems, the *TI Magnetic Sense Simulator* (TIMSS) tool can accelerate design and evaluation of magnetics systems.

Keep the airgap at 0.8mm and collect 30000 angle samples over one revolution. The rotary accuracy is shown in Figure 4-14. The peak to peak error is 0.28° without any offset and gain calibration. By using post-calibration to compensate 1^{st} and 2^{nd} harmonic, the error can be reduced to +/-0.032°, which is shown in Figure 4-14.

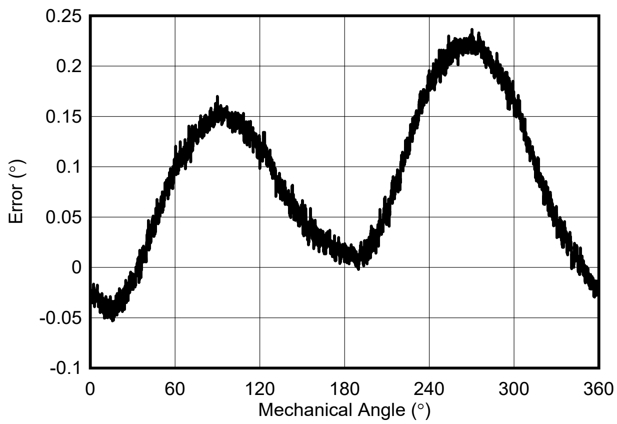


Figure 4-14. Uncalibrated Rotary Angle Accuracy at 0.8mm Airgap

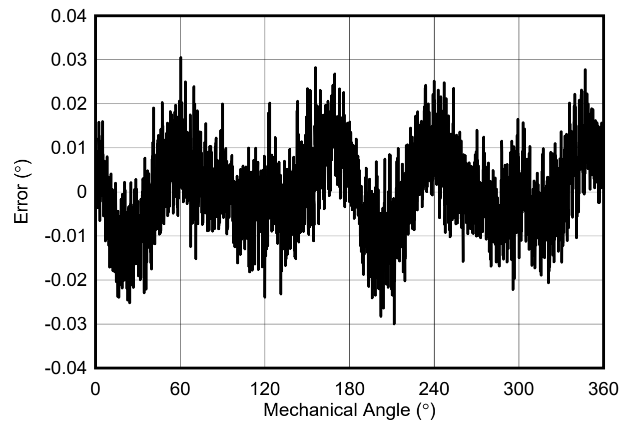


Figure 4-15. Rotary Angle Accuracy with Offset Calibration at 25°C Ambient

To do the repeatability test, continuously sample the angle data over two revolutions. After using same calibration parameter, compare the calibration results of two cycles. Figure 4-16 shows the results. Cycle1 and cycle2 data almost complete overlap, this means the good repeatability of TIDA-010947.

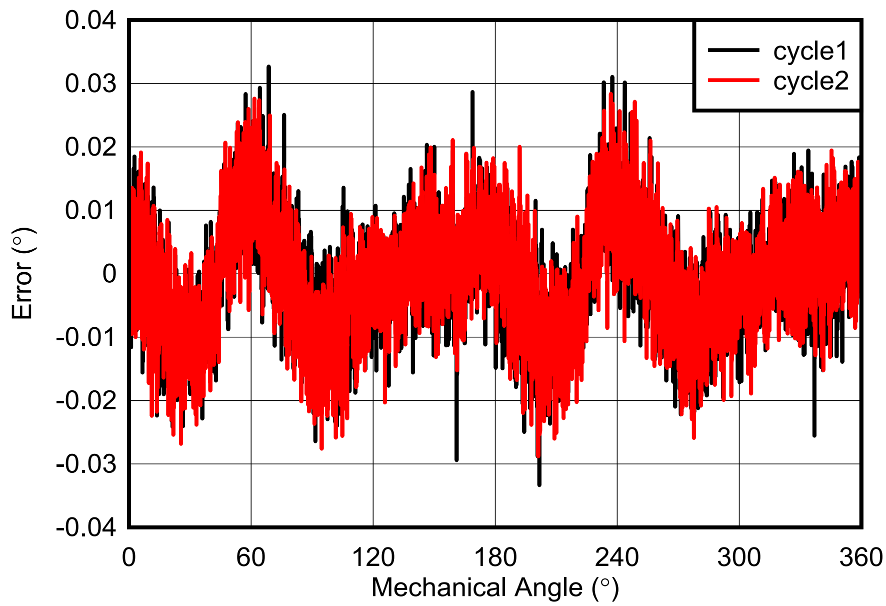


Figure 4-16. Rotary Angle Accuracy with Offset Calibration at 25°C Ambient, Repeated Test Run

4.3.3.1 Impact of Airgap on Noise, Harmonics, and Total Angle Accuracy

With the airgap increasing, the magnetic field can reduce and leads to higher noise of position sensor. This section analyzes the airgap's influence on TIDA-010947. By using gasket, the airgap changes from 0.3mm to 2.3mm. Repeat the test procedure described in Section 4.3.3, the test results are shown in Figure 4-17 to Figure 4-20. Under all airgap, the error with calibration are lower than ±0.037°.

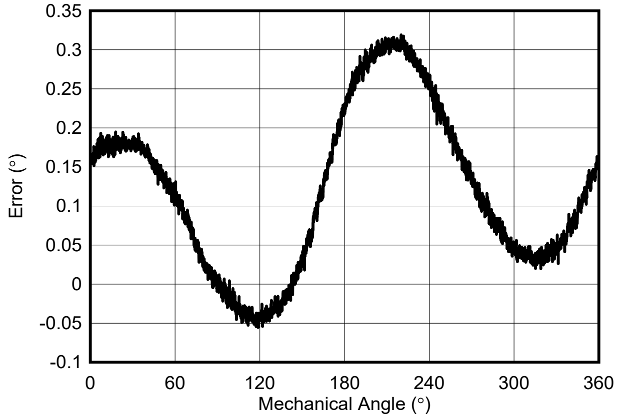


Figure 4-17. Uncalibrated Rotary Angle Accuracy with Calibration at 0.8mm Airgap

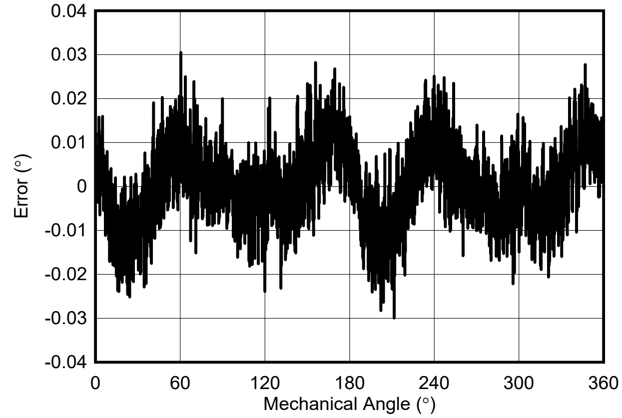


Figure 4-18. Rotary Angle Accuracy with Calibration at 0.8mm Airgap

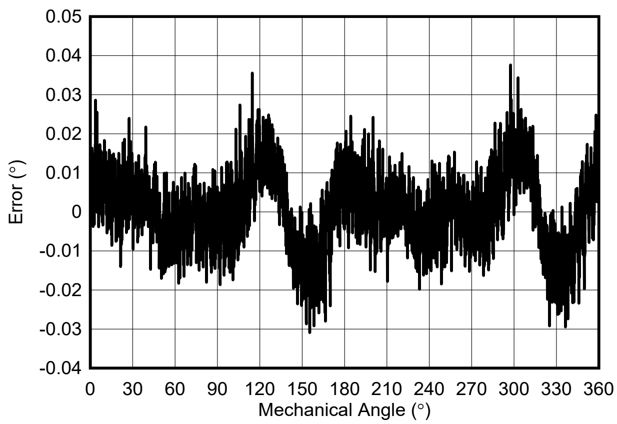


Figure 4-19. Rotary Angle Accuracy with Calibration at 1.3mm Airgap

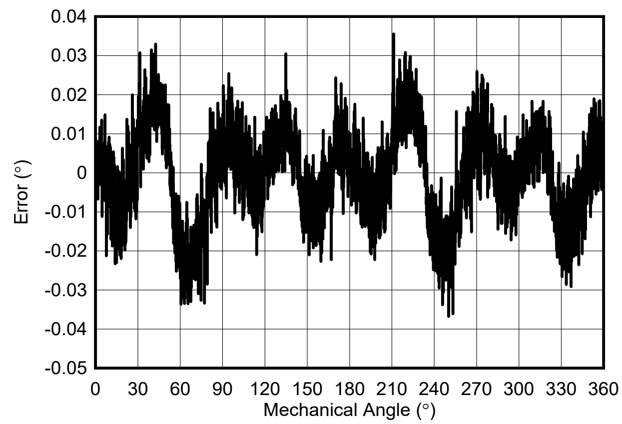


Figure 4-20. Rotary Angle Accuracy with Calibration at 2.3mm Airgap

To further analyze the airgap influence on harmonics, FFT analysis is used. The results are listed on the Table 4-9. 4th harmonic is from signal chain gain mismatch, which is not influenced by airgap. 8th harmonic is caused by AMR sensor and signal chain's non linearity, higher airgap can lead to increasing value of the 8th harmonic.

Table 4-9. Angle Error and Harmonics vs Airgap

Airgap	Offset calibrated angle error [°]	4th harmonic [°]	8th harmonic [°]
0.3mm	<0.04°	0.0086	0.0015
0.8mm	<0.04°	0.006	0.0012
1.3mm	<0.04°	0.0062	0.0041
2.3mm	<0.04°	0.0058	0.0113

4.3.4 RS485 Interface and Signal Integrity

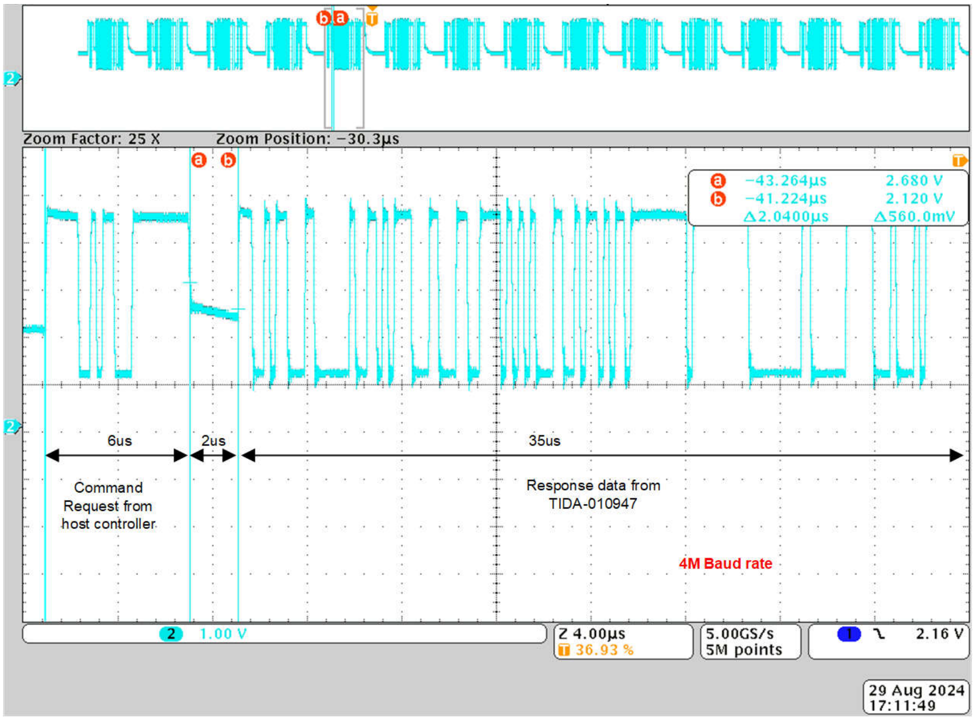


Figure 4-21. Timing Diagram (Tamagawa T-format) to Request New Angle Data

Figure 4-21 shows the communication timing diagram between host controller and TIDA-010947. The communication is based on T-format protocol. The host controller sends a command request every 62.5us (32kHz), TIDA-010947 responds with the corresponding angle data within 2us. The request command takes 6us and response data takes 35us.

In Figure 4-22 shows the rise and fall time of RS485 signal, which are around 40ns. Since UART baud rate is 4M, 1bit signal can last 250ns, so the rise and fall time do not influence communication.

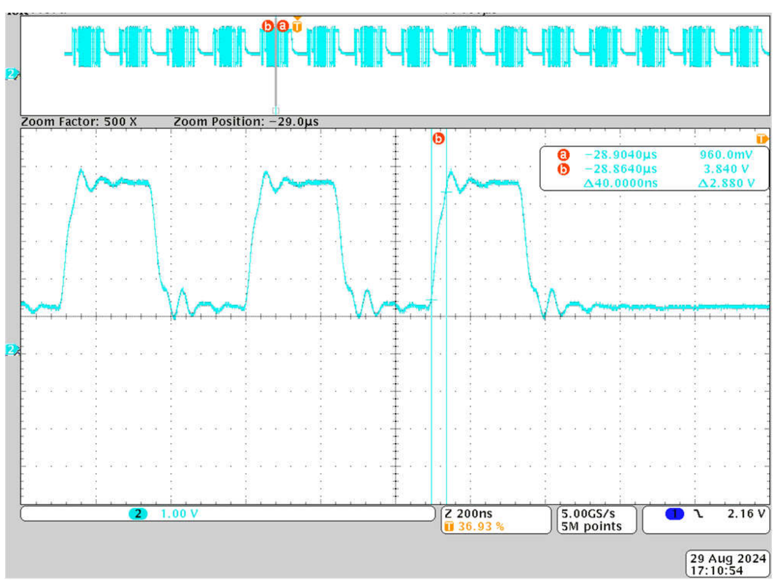


Figure 4-22. RS485 Signal Rise and Fall Time

5 Design and Documentation Support

5.1 Design Files

5.1.1 Schematics

To download the schematics, see the design files at TIDA-010947

5.1.2 BOM

To download the bill of materials (BOM), see the design files at TIDA-010947

5.1.3 PCB Layout

To download the PCB layout, find the design files at TIDA-010947

5.1.4 Altium Project Files

To download the Altium Project Files, find the design files at TIDA-010947

5.1.5 Gerber Files

To download the Gerber Files, find the design files at TIDA-010947

5.1.6 Assembly Drawings

To download the Assembly Drawings, find the design files at TIDA-010947

5.2 Tools and Software

Tools

TI-MAGNETIC-SENSE-SIMULATOR Magnetic simulation software that includes mechanical motion and sensor output.

Software

MSPM0-SDK The MSPM0 SDK provides the ultimate collection of software, tools and documentation to accelerate the development of applications for the MSPM0 MCU platform under a single software package.

MSP-IQMATHLIB The Texas Instruments® MSP IQmath and Qmath Libraries are a collection of highly optimized and high-precision mathematical functions for C programmers to seamlessly port a floating-point algorithm into fixed-point code on MSPM0, MSP430 and MSP432 devices.

5.3 Documentation Support

1. Texas Instruments, *Calibration of AMR Angle Sensors*, application note.
2. Texas Instruments, *Achieving Highest System Angle Sensing Accuracy*, application note.
3. Texas Instruments, *Introduction to TI Magnetic Sense Simulator Features*, application brief.
4. TAMAGAWA SEIKI, *Rotary Encoders Catalog*, product catalog

5.4 Support Resources

TI E2E™ support forums are an engineer's go-to source for fast, verified answers and design help — straight from the experts. Search existing answers or ask your own question to get the quick design help you need.

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