TMR FOR 2D ANGLE SENSING

By Allegro MicroSystems

ABSTRACT

This paper discusses the construction and operational principle of Allegro TMR-based angle-sensing technology. The main sources of angle error in two-dimensional (2D) sensors are explained.

XMR FOR AUTOMOTIVE AND INDUSTRIAL APPLICATIONS

Although xMR-based sensors are relatively new, they have already entered various industrial and automotive applications. Due to the magnetic measurement principle, high sensitivity, and low noise, they are very well suited for a wide range of different applications in the field of angle and speed sensing (see Figure 1). Examples of the target applications in industrial and automotive environments are:

- Steering angle measurement.
- Rotor position measurement for motor communication in a brushless-DC (BLDC) motors.
- Speed sensing for wheel speed measurements (ABS sensor).
- Crank shaft speed and position sensing with direction data.

To address these applications, Allegro developed a special TMR angle sensor (2D sensor) that can provide data about the shaft angle, rotation direction, and rotation speed in real time.

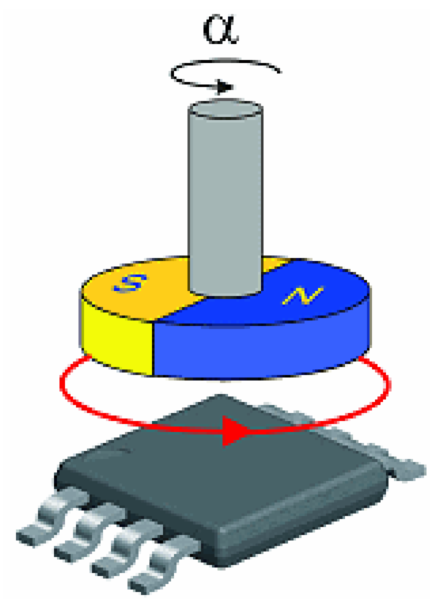


Figure 1: Angle Sensor Measures Magnetic-field angle of Shaft End

Allegro TMR angle sensing uses the same physical principle as other TMR/GMR-based magnetic sensors. The basic construction unit of the TMR magnetic sensor is a magnetic tunnel junction (MTJ) that consists of a pinned and free (sense) layers separated by a dielectric barrier (see Figure 2). If the external magnetic-field changes, the sense layer magnetization changes its magnitude and orientation. This leads to changes in the MTJ resistance.

However, there is one important difference between a TMR angle sensor and a TMR linear magnetic sensor. A TMR sensor usually works in the linear range of TMR characteristics (see Figure 2), whereas an angle sensor is in the saturated region. In other words, magnetization of the sense layer is always at the maximum possible magnitude and changes its orientation vector together with the external magnetic-field angle. The sense layer is kept always in saturation in order to achieve the best possible performance indicators, as discussed in the next section. The obvious limitation of such an approach is that the angle sensor cannot operate at low magnetic fields. The operational magnetic-field range of a typical angle sensor is generally between 25 mT and 90 mT.

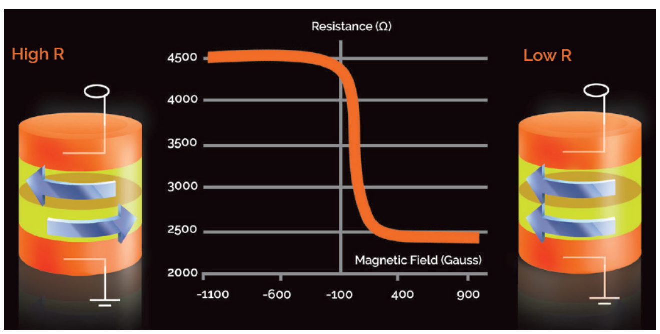


Figure 2: TMR Physical Principle for Single MTJ—MTJ Resistance Depends on Magnitude of External Magnetic Field

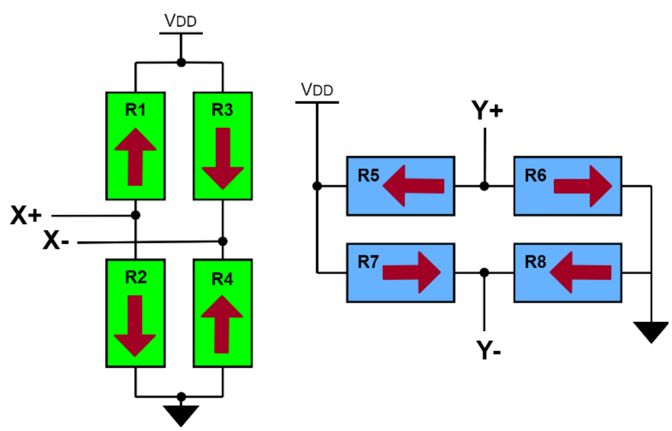
TMR ANALOG 2D SENSOR

Basic Construction

A TMR angle sensor (2D sensor) consists of eight TMR resistors that are sensitive to the magnetic field. Each resistor is constructed from a number of MTJs (TMR elements). Eight resistors are connected into two Wheatstone bridge circuits, four resistors in each bridge circuit (see Figure 3). Every TMR resistor is preprogrammed magnetically, so it is sensitive to the magnetic field in certain directions. Moreover, two neighboring branches are configured to change resistances with opposite signs to each other. For example, R1 and R2 in Figure 3 change values in opposite directions while external magnetic field is applied. As a result, a TMR angle sensor consists of two bridges that are sensitive to linear components of an external magnetic field that is perpendicular to each other's direction.

Essentially, each full bridge is a linear magnetic sensor designed to measure a projected external magnetic field on its axis of sensitivity. The sensitivity axes of X and Y bridges are designed and implemented to be perfectly 90° to each other.

Both bridges are designed to be biased with constant V_{DD} voltage, as shown in Figure 3. The output of each sensor consists of two differential voltage signals: X and Y.



R1, R2, R3, R4 Wheatstone bridge is sensitive to north/south orientation of magnetic field (X). R5, R6, R7, R8 Wheatstone bridge is sensitive to east/west orientation of magnetic field (Y).

Figure 3: Basic Construction of TMR Angle Sensor.

Principle of Operation and Calibration

The operation principle of a TMR angle sensor is based on the fact that two bridges, X and Y, provide harmonics that are identical to each other's voltage response versus the magnetic-field angle but shifted 90° to each other. In other words, the X bridge response is a sine function of the magnetic-field angle and the Y bridge response is a cosine function (see Figure 4).

It is always necessary to bias each bridge with a V_{DD} voltage that is between 1 V and 5.5 V. The response of each bridge is measured in volts and characterized in volts per bias voltage.

Both bridges separately provide measurement of only one half of the external magnetic-field angle range, as shown in Figure 4. For example, the X bridge has the same voltage response for 45° and 135° magnet positions. A full 0° to 360° angle-range measurement is obtained by performing a simple arctangent operation with X and Y responses:

$$a = \arctan(Y/X)$$

The X and Y bridges of the angle-sensor responses are differential analog voltage signals. In most cases, it is necessary to convert differential signals into a single-ended signal before the arctangent calculation. In certain applications, additional signal correction and conditioning are necessary to achieve better sensor performance (see the Angle Error section). In Figure 5, the "Amp X" and "Amp Y" blocks schematically represent readout circuits needed for proper X and Y signals acquisition and conditioning before the arctangent calculation.

There are three methods to calculate the arctangent with X and Y signals from the xMR angle sensor. These methods use either a microcontroller (MCU) or a coordinate rotation digital computer (CORDIC).

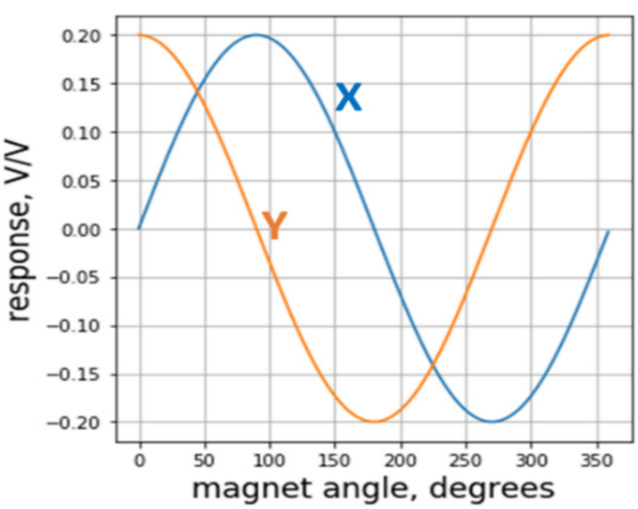


Figure 4: X and Y Bridge Response as Function of External Magnetic-field angle

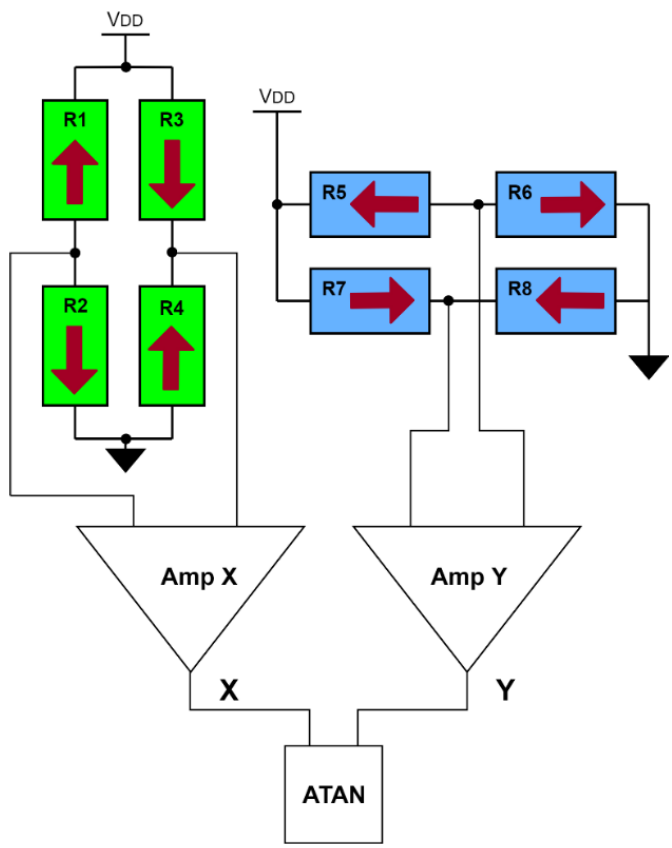


Figure 5: X and Y Bridges of TMR Angle Sensor, Together with Readout Circuit Block Diagram and Arctangent Calculation Block

Angle Error

The TMR angle sensor is designed to achieve precise measurement of uniform magnetic-field angles. By far, the most critical parameter of any angle sensor is the angle error. Angle error, as a function of the angle measured at a constant field and constant temperature, is presented for a typical Allegro TMR angle sensor in Figure 6. The angle error versus the measured angle dependence consists of a number of sine and cosine harmonics that arise due to certain magnetic imperfections in the TMR magnetic layers. Internal magnetic and electric properties of TMR magnetic layers have various dependencies due to temperature changes across all field magnitudes within a working range. With its proprietary and patented TMR-based magnetic technology, an Allegro TMR 2D sensor achieves superior angle error. The amplitude of angle-error dependence (as shown in Figure 6) is usually used as a figure of merit for the maximum angle error at a given magnetic-field magnitude and temperature point. For example, the angle-error dependence in Figure 6 was measured at 40 mT field and at room temperature (25°C).

Allegro proprietary XtremeSense™ technology allows TMR 2D sensor angle-error values to be below 0.6° within the whole working field range, from 25 mT up to 90 mT. The typical angle error versus magnetic-field dependence is illustrated in Figure 7.

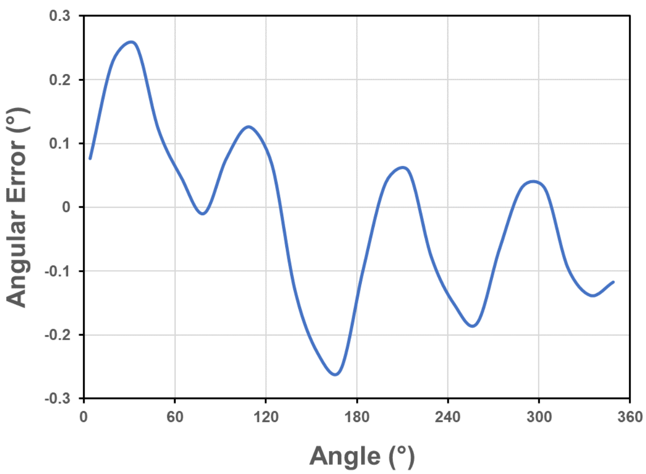


Figure 6: Example of Angle Error (AE) as a Function of Magnetic-field angle Measured at Room Temperature at a Single Magnitude Rotating Magnetic Field

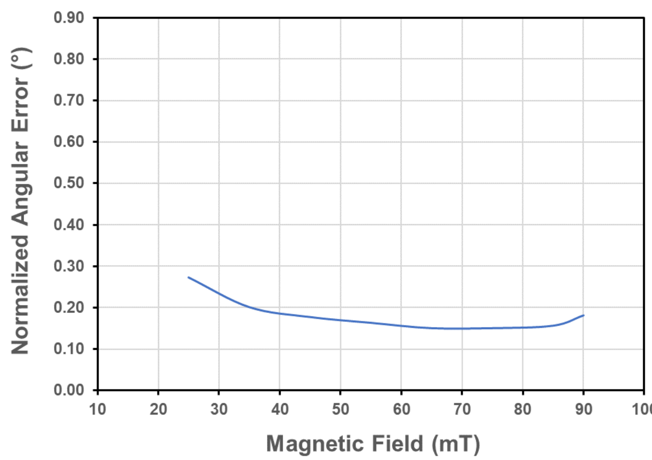


Figure 7: Example of Normalized Angle Error versus Magnitude of a Rotating Magnetic Field Measured at Room Temperature

IMPLEMENTING CT310 IN SYSTEMS

To implement the CT310, both bridges (COS and SIN) should be powered simultaneously with identical V_{DD} voltages in the range of 1 V to 5.5 V, as indicated in the recommended application circuit in the CT310 datasheet (see Figure 8); electrostatic-discharge (ESD) protection is already implemented inside of the CT310 sensor circuitry.

The outputs from both bridges (COSP, COSN and SINP, SINN) are differential analog signals, and—to allow numerical arctangent calculations (see the Principle of Operation and Calibration section)—these signals should be digitized first.

The first way to digitize the sensor signal is to connect them to differential input analog-to-digital converters (ADCs), one ADC per each bridge output. However, differential ADCs are not always available, especially in the case of microcontroller systems. A regular single-ended ADC could be used if signals are brought to single-ended modes using instrumentation amplifiers (see Figure 8). In case of battery-powered applications, where voltages are DC, it is necessary to shift the reference voltage point on the instrumentation amplifier (INA) to the level of $V_{DD}/2$, which allows differential signals to be always above 0 V.

Standard inverse-tangent-function return-angle values range from –90° to 90°. For this application, it is important to use a four-quadrant arctangent function to return an angle from –180° to +180°. This function also avoids issues with dividing by 0. Four-quadrant inverse tangent functions are listed in Table 1.

Table 1: Arctangent Functions for MATLAB, ARDUINO, C#, and Python Programs

Program	Function	Description
MATLAB	atan2(Y,X)	Result in radian
	atan2d(Y,X)	Result in degrees
ARDUINO	atan2(Y,X)	Returns double
	atan2f(Y,X)	Returns float
C#	Atan2(Y,X)	Returns double
Python	NumPy.arctan2(Y,X)	Returns double

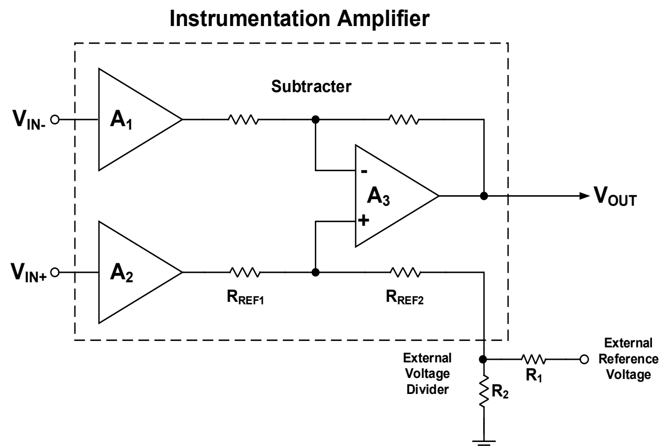


Figure 8: Conversion of Differential Analog Signal into Single-Ended Signal with Reference Voltage Shift on the INA

CONCLUSION

Allegro TMR-based 2D sensors offer the best alternative to older magnetic 2D sensors. Advantages include: lowest power consumption, low angle error, and cost-effectiveness due to the high CMOS-integration capability that enables a monolithic integrated circuit.

Revision History

Number	Date	Description	Responsibility
1	November 15, 2023	Document rebrand and minor editorial corrections	J. Henry