TMR FOR PRECISION LINEAR MEASUREMENT

By Allegro MicroSystems

ABSTRACT

This paper covers the construction and operational principle of tunnel magnetoresistance (TMR)-based one-dimensional (1D) magnetic sensors produced by Allegro.

XMR FOR AUTOMOTIVE, CONSUMER, AND INDUSTRIAL APPLICATIONS

Although xMR-based sensors are relatively new, they have already entered various consumer, 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 linear-motion sensing (see Figure 1). Examples of the target applications in consumer, industrial, and automotive environments are:

- HVAC vent position reporting
- Robotic arm motion tracking
- Linear table positioning
- Lens focusing systems
- Power seat movement
- Sliding door position feedback
- Linear encoders
- Materials and food processing equipment
- Bottling/sorting equipment
- Slider/joystick positioning

Allegro TMR magnetic sensors work under the same physical principle as all the other anisotropic-magnetoresistance/giant-magnetoresistance (AMR/GMR) based magnetic sensors. The basic construction unit of a TMR magnetic sensor is a magnetic tunnel junction (MTJ), which consists of a pinned layer and a free (sense) layer separated by a dielectric barrier (see Figure 2). if the external magnetic field changes, the magnetization of the sense layer changes its magnitude and orientation, which leads to changes in the MTJ resistance.

However, there is one important difference between a TMR angle sensor and a TMR linear magnetic sensor: TMR sensors usually work in the linear range of TMR characteristics (see Figure 2), whereas angle sensors usually work in the saturated region. In other words, the sense-layer magnetization 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 magnetic sensor cannot operate at low magnetic field. The typical 2D magnetic-sensor operational magnetic-field range is 20 mT to 80 mT.

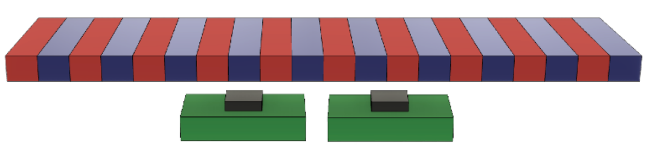

Figure 1: Linear Motion Measurement Between Two 1D Magnetic Sensors and Magnetic Strip.

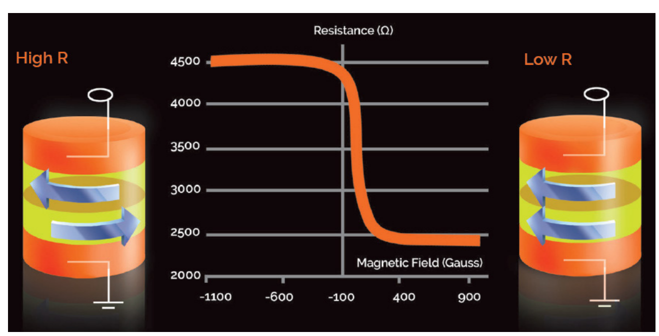

Figure 2: Physical Principle of TMR for Example of Single-MTJ—MTJ Resistance Depends on Magnitude of External Magnetic Field

TMR ANALOG 1D SENSOR

Basic Construction

The sensor bridge is designed to be biased with constant V_{DD} voltage, as shown in Figure 3. A TMR 1D magnetic sensor consists of four TMR resistors that are sensitive to a magnetic field. Each resistor is constructed from a number of MTJs (TMR elements). Four resistors are connected in a Wheatstone bridge circuit (see Figure 3).

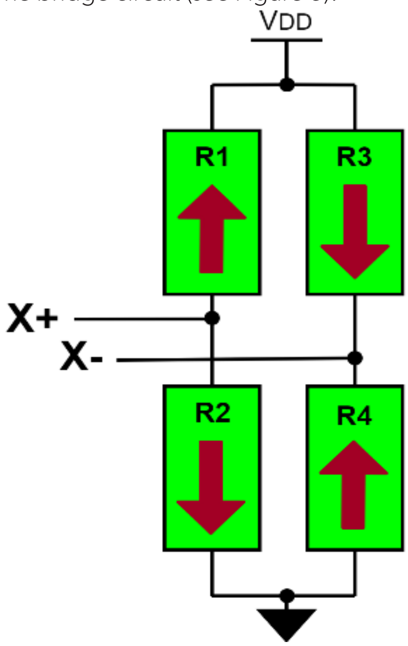

Figure 3: Basic Construction of TMR Magnetic Sensor—R1, R2, R3, R4 Wheatstone Bridge is Sensitive to North/South Orientation of Magnetic Field (X)

Principle of Operation and Calibration

When a magnetically polarized strip (see the Mechanical Considerations section) travels along the axis of sensitivity of two properly positioned 1D sensors, the sensor outputs produce two wave forms that are 90 degrees out of phase from each other (see Figure 4).

It is always necessary to bias each bridge with a V_{DD} voltage that is between 1 V and 5 V. The response of each bridge is measured in volts and characterized in volts per bias voltage.

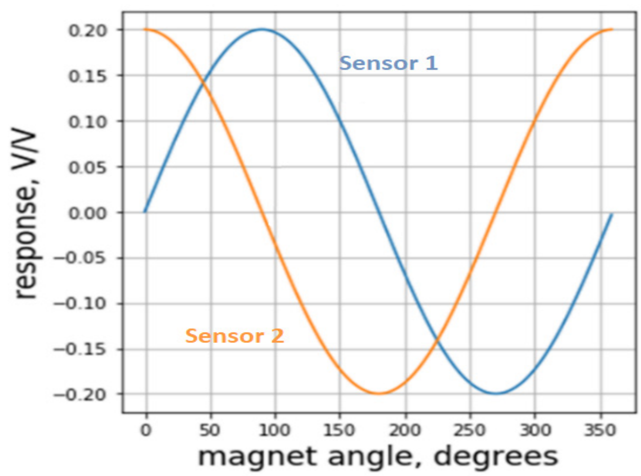

Figure 4: Sensor Response as Function of Magnetic Strip Traveling Along Sensor Axis of Sensitivity

Mechanical Considerations

Properly positioned CT100 sensors in close proximity to the moving strip produce electrical output signals that are out of phase by 90 degrees. Each sensor should be placed with its axis of sensitivity in parallel to the direction of the magnetic strip movement. The recommended distance between CT100 sensors can be calculated by using:

$$d = 2ne + (e/2),$$

where:

- d is the distance between sensors.
- e is the pitch of the magnetic strip (distance between north and south poles).
- n is any integer value that provides adequate mounting space between sensors.

Because the field dynamic range of the CT100 is ±20 mT, selecting the correct magnetic strip is important to prevent exceeding the maximum range of the sensor. Excessive distance and/or weak magnets may produce magnetic fields that are insufficient for reliable distance calculations. The distance, or air gap, between the strip and TMR sensors is also important in producing the desired sine (sin) and cosine (cos) waveforms. Air gap calculations should also factor in any vibrations that may occur within the system.

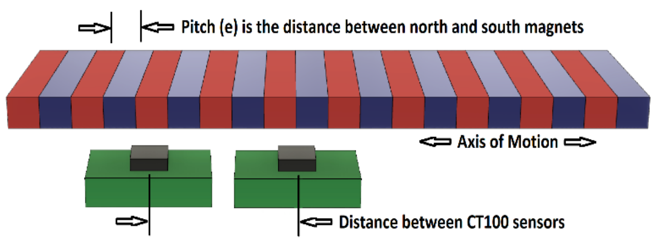

Figure 5Figure 5. Placement of Two CT100 Magnetic Sensors

Calculating Distance of Motion

The change in the position of the magnetic strip is calculated by comparing the sensor output voltages with the previously measured sensor voltages and applying the arctan2 function. The distance (d) traveled by the magnetic strip can be calculated using:

$$d = \frac{(n-1) \cdot arctan2(sin, cos) - \mathrm{n} \cdot \mathrm{arctan2(sin, cos)} \cdot \mathrm{e}}{\pi}$$

where:

- e is the pitch, which is the distance between north and south magnetics embedded in the linear strip.
- n is the current sample number.
- n – 1 is the previous sample number.

Sine is the output voltage from sensor 1, and cosine is the output voltage from sensor 2. Both outputs are normalized to a range of ±1 V.

For example:

- e is 2 mm (pitch of the magnetic strip).
- Last measured voltage is +0.2079 V for sensor 1 and +0.9781 V for sensor 2.

$$\therefore arctan2(0.2079, 0.9781) = 1.34390$$

- Currently measured voltage is +0.2249 V for sensor 1 and +0.9722 V for sensor 2.

$$\therefore arctan2(0.2249, 0.9722) = 1.32645$$

$$d = \frac{1.343904 - 1.32645}{3.14159} \cdot 2\ mm$$

$$d = +0.01111\ mm$$

IMPLEMENTING CT100 SENSORS IN SYSTEMS

The outputs from both CT100 sensors are differential analog signals; and to allow numerical arctangent calculations (see Table 1), these signals should be digitized first.

One approach to digitizing the sensor signal is to connect them to differential-input ADCs, with one ADC for each bridge output. However, differential ADCs are not always available, especially in the case of microcontroller systems. If signals are brought to single-ended modes using instrumentation amplifiers, a regular single-ended ADC can be used (see Figure 6). In the case of battery-powered applications, where voltages are DC, it is necessary to shift the reference voltage point on INA to the level of $V_{DD}/2$. That will allow differential signals to be always above 0 V.

Because the acrtan2 value changes sign, errors can occur when the phase angle crosses 180°. Subtracting arctan2 values of different signs yields incorrect results. Calculation routines should check the sign of both arctan2 results before subtraction.

Standard inverse tangent functions return angle values ranging 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 zero. 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

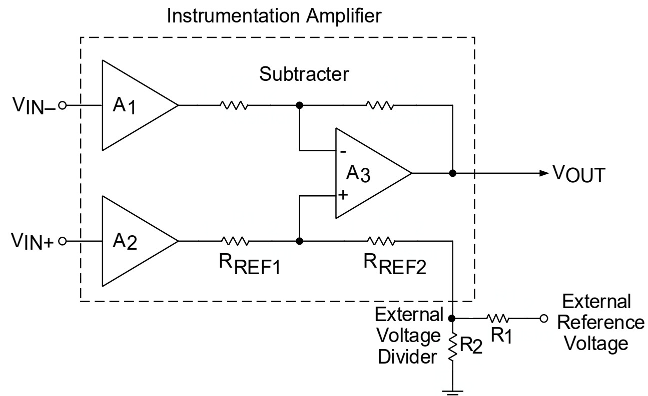

Figure 6: Conversion of Differential Analog Signal into Single-Ended Signal with Reference Voltage Shift on INA.

CONCLUSION

Allegro TMR-based 1D sensors offer the best alternative to older magnetic sensor technologies. Advantages include lowest power consumption, low linearity error, and a cost-effective solution due to the high CMOS integration capability, which enables a monolithic integrated circuit.

Revision History

Number	Date	Description	Responsibility
1	November 14, 2023	Document rebrand and minor editorial corrections	J. Henry

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955 PERIMETER ROAD • MANCHESTER, NH 03103 • USA
+1-603-626-2300 • FAX: +1-603-641-5336 • ALLEGROMICRO.COM