TMR for Precision Linear Measurement

1 Abstract

This paper covers the construction and operational principle of Tunnel Magneto-Resistance (TMR)-based one dimensional (1D) magnetic sensors produced by Crocus Technology.

2 xMR for Automotive, Consumer, and Industrial Applications

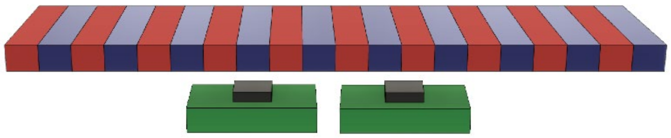

Figure 1. *Linear motion measurement between two 1D magnetic sensors, and magnetic strip.*

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

Crocus' TMR magnetic sensors works under the same physical principle as all the other AMR/GMR-based magnetic sensors. The basic construction unit of TMR magnetic sensor is a Magnetic Tunnel Junction (MTJ) which consists of a pinned and free (sense) layers separated by a dielectric barrier (see Figure 2). The sense layer magnetization changes its magnitude and orientation if the external magnetic field changes occur. That leads to changes in the MTJ resistance.

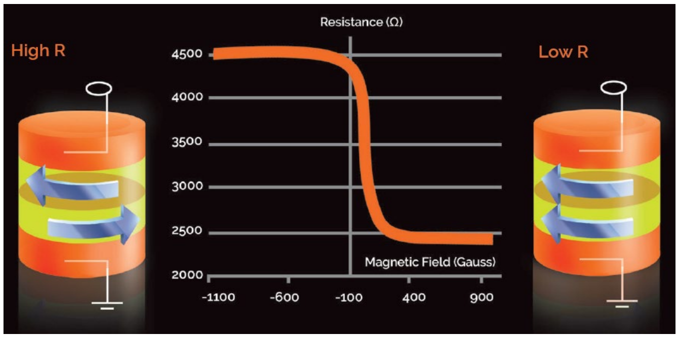

Figure 2. *TMR physical principle for the example of a single Magnetic Tunnel Junction (MTJ). The MTJ resistance depends on the magnitude of the external magnetic field.*

However, there is one important difference between a TMR angular sensor and a TMR linear magnetic sensor. TMR sensors usually work in the linear range of TMR characteristics (see Figure 2) whereas the angle sensor is 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 which will be discussed in the next section. The obvious limitation of such approach is that the magnetic sensor can't operate at low magnetic fields. The typical 2D magnetic sensor's operational magnetic field range is between 20 mT and 80 mT.

3 TMR Analog 1D Sensor

3.1 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 (4) resistors are connected in a Wheatstone bridge circuit (see Figure 3).

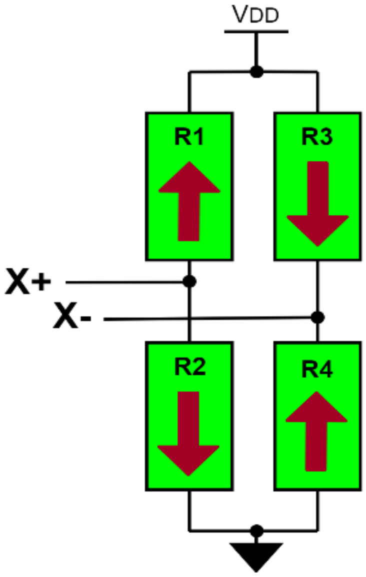

Figure 3. *Basic construction of TMR Magnetic sensor. R1, R2, R3, R4 Wheatstone bridge is sensitive to north/south orientation of magnetic field (X).*

3.2 Principle of Operation and Calibration

When a magnetically polarized strip (see figure 5) travels along the axis of sensitivity of two properly positioned 1D sensors, the sensor outputs will produce two wave forms that are 90 degrees out of phase from each other (see *Figure 4*).

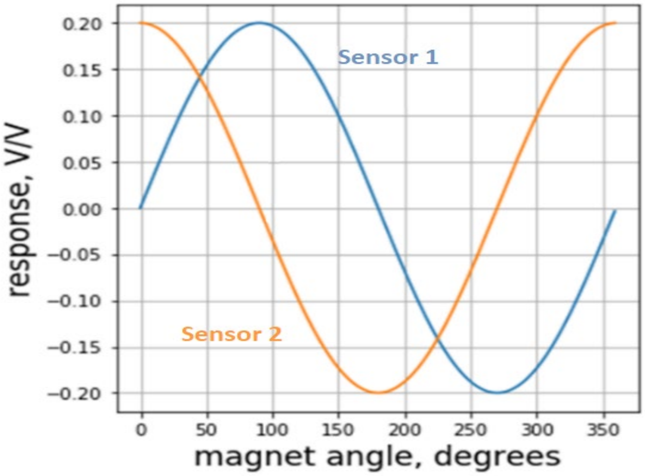

Figure 4. *Sensor 1 and Sensor 2 response as a function of a magnetic strip traveling along the sensor's axis of sensitivity.*

It is always necessary to bias each bridge with a V_{DD} voltage that is between 1.0 V and 5.0 V. Each bridge's response is measured in Volts and characterized in Volts per bias Voltage.

3.3 Mechanical Considerations

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

$$d = 2ne + \frac{e}{2}$$

where:

d = the distance between sensors

e = the pitch of the magnetic strip (distance between N and S poles)

n = any integer value which provides adequate mounting space between the sensors.

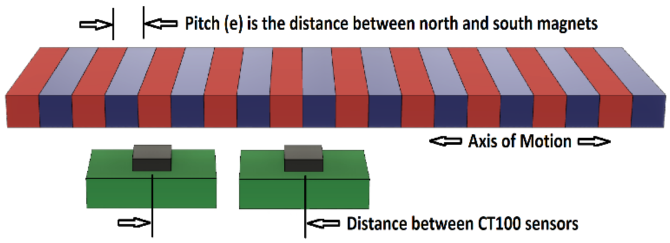

Figure 5. *Placement of two CT100 magnetic sensors.*

Since the field dynamic range of the CT100 is ±20mT, 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.

3.4 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 following equation can be used to calculate the distance (d) traveled by the magnetic strip.

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

e = the pitch is the distance between north and south magnetics embedded in the linear strip

n = current sample number

n – 1 = 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 = 2 mm (pitch of the magnetic strip)

Last measured sensor #1 voltage was +0.2079 V, and sensor #2 voltage was +0.9781 V.

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

Current measured sensor #1 voltage is +0.2249 V, and sensor #2 voltage is +0.9722 V.

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

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

$$d = +0.01111\,mm$$

4 Implementing CT100 Sensors in Systems

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

One approach to digitizing the sensor's 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, epecially 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 6). In case of battery-powered applications, where voltages are DC it is necessary to shift the reference voltage point on INA to $V_{DD}/2$ level. That will allow differential signals to be always above 0 V.

Errors can occur when the phase angle crosses 180° as the *acrtan2* value will change sign. Subtracting *arctan2* values of different signs will yield 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 (4) quadrant arctangent function to return an angle from -180° to +180°. This function also avoids issues with dividing by zero (0). Four (4) quadrant inverse tangent functions are listed in the table below.

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

Table 1. *Arctangent functions for MATLAB, ARDUINO, C# and Python programs.*

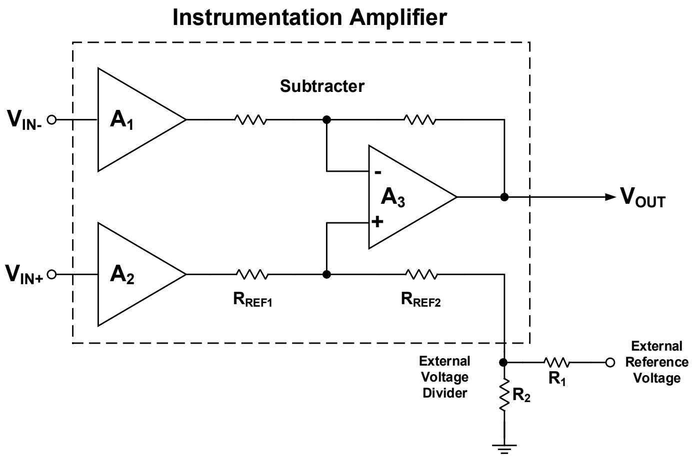

Figure 6. *Conversion of differential analog signal into single-ended one with reference voltage shift on INA.*

5 Conclusion

Crocus Technology's TMR based 1D sensor offers 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 IC (integrated circuit).