LEVERAGING MAGNETIC SENSITIVITY FOR BETTER DEVICE DESIGN

The Role of Magnetic Sensors & Sensitivity in Position Sensing,
Level Sensing, Rotary Sensing and more

INTRODUCTION

Understanding the role and behavior of digital magnetic sensors and sensitivity is essential in order to achieve cost-effective design of electronic applications within major markets such as industrial automation, white goods, security and metering. Typical applications for sensors within these markets include level sensing, position or proximity sensing and revolution counting.

The degree of magnetic sensitivity of a sensor can affect the number of sensors required within a device, the grade/cost needed for a magnet as well as the distance and range for activation or detection. Magnetic sensitivity also affects resolution and precision. A basic understanding of magnetic units (Gauss or Tesla), the sensor's magnetic sensitivity, and the importance of orientation with regard to angle will assist engineers in specifying the best magnetic sensor/magnet pairing for their device design. Coto Technology has comprehensive knowledge in the topic of magnetic sensitivity; therefore, Coto's Tunneling Magnetoresistance (TMR) magnetic sensors are featured in this generalized explanation of magnetic sensitivity

TMR sensors are an emerging technology for detecting and quantifying the magnitude of a magnetic field; they offer several advantages over earlier types of magnetic sensors, including extremely low power consumption, high magnetic sensitivity, robustness and small size.

TMR sensors have very high magnetic sensitivity (ability to detect very small magnetic fields) and very low power consumption – in some cases down to tens of nanowatts depending on their design.

RedRock® TMR Digital Sensors: Magnetic Sensitivity

Overview

Digital sensors turn ON when the magnitude of the magnetic field (B) surrounding them exceeds a threshold value defined as B_{OP}, and turn OFF when the field drops below a second threshold defined as B_{RP}. The threshold levels are set using comparator circuits and are fixed for a specific product family. Typical levels are $B_{OP} = 30$ Gauss and $B_{RP} = 20$ Gauss, or $B_{OP} = 9$ Gauss and $B_{RP} = 5$ Gauss. On the other hand, analog sensors do not have internal threshold comparators, and instead provide a voltage output signal which is linearly proportional to the applied magnetic field over a defined range of field magnitude. The functional block diagrams of digital and analog sensors are shown in Figure 1 and Figure 2 respectively.

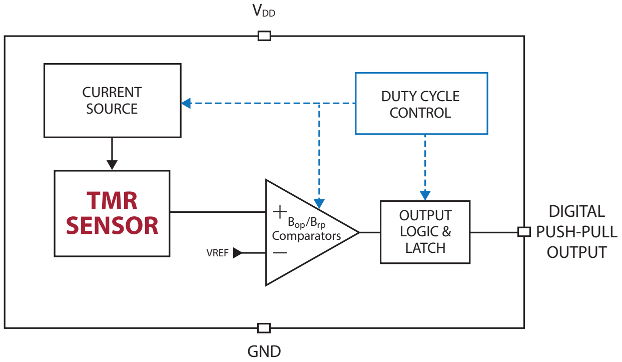


Figure 1: Functional block diagram of a RedRock® digital TMR sensor with push-pull output

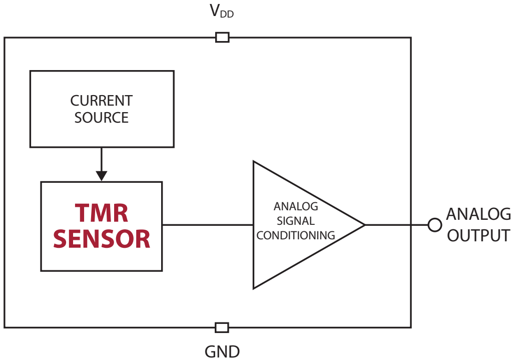


Figure 2: Functional block diagram of a RedRock® analog TMR sensor

Magnetic Units – Gauss or Tesla?

In its product literature, Coto Technology uses units of Gauss (abbreviated to G) to specify the magnitude of magnetic flux density. Magnetic flux density is often referred to as the B-field. Thus a digital sensor that turns ON when the magnetic flux density surrounding it exceeds, for instance, 10 Gauss is said to have a B operate point of 10G.

Gauss units are frequently used in the USA. Most other countries now use SI units to specify magnetic flux density. The corresponding unit is the Tesla. Since this a rather large unit, millitesla (usually abbreviated to mT) are more common. One mT is exactly equivalent to 10G. Magnetic flux density is often simply referred to as magnetic field or magnetic field strength, though this terminology is technically incorrect.

Another unit often encountered in the magnetics field is the Oersted, the unit of magnetic field strength in what is called the H-field. Oersteds and Gauss are related to each other through the relationship $B = \mu H$, where μ = magnetic permeability, which is 1 in a vacuum and extremely close to 1 in air. However, in a material that has high magnetic permeability such as iron, the magnetic flux density (B) induced in the material may be hundreds or thousands of times greater than the magnetic field (H) inducing it. The equivalent unit for H in the SI system is the amp/meter (A/m or $A \cdot m^{-1}$)

Specifying Magnetic Sensitivity

The magnetic sensitivity of digital RedRock® sensors is defined as B_{OP}, the magnetic field level at which the sensor turns ON, and B_{RP}, the level at which the sensor turns OFF. These levels may be further divided into B_{OPN} and B_{OPS}, and B_{RPN} and B_{RPS}, where the "N" and "S" suffixes refer to North or South fields. The sensitivity levels have a certain degree of variance; for example, a group of sensors with a nominal B_{OPN} value of 30G may vary from a minimum of 27G to a maximum of 38G. The typical, minimum and maximum values for the B-parameters B_{OPN}, B_{RPN}, B_{OPS} and B_{RPS} are listed in the product data sheets for each RedRock® sensor family. On the other hand, the magnetic sensitivity of analog sensors such as the RedRock® RR112 family is defined differently.

Sensitivity vs. Angle

It is common practice to place an activating magnet on the sensor's principal axis of magnetic sensitivity, since this orientation yields the maximum sensitivity for a given magnet size. However, RedRock® TMR sensors have significant off-axis sensitivity, and this can be revealed by magnetic sensitivity diagrams projected onto different planes. The diagrams are commonly called "lobe diagrams," perhaps from their similarity to radio-frequency antenna field strength plots. Angular sensitivity can be shown two different ways in a polar diagram.

In Figure 3, the operate and release sensitivities for a RedRock® sensor are plotted in Gauss vs. magnetic field angle. The solid red line shows the operate field and the dotted red line shows the release field. Clearly there is a null response between approximately 15° and 345°, and also between 165° and 195°, and the highest sensitivity occurs around 90° and 270°, when the magnetic field is aligned with the long axis of the SOT-23 package. This type of plot is "universal" in that it is not tied to one particular magnet. However, the data is perhaps easier to interpret if the operate and release field values are converted to operate and release distances.

Operate and Release Field Strength vs. Angle

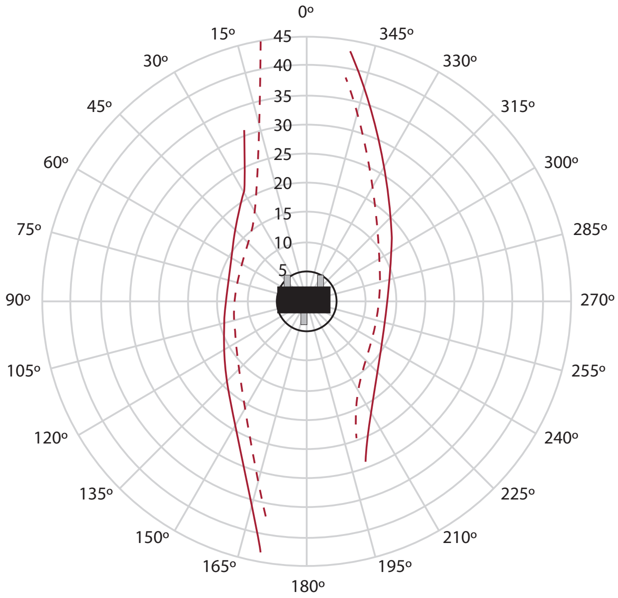


Figure 3: Operate and Release field strengths (G) for an omnipolar RedRock® sensor vs. magnetic field angle. Solid red line = operate, dotted red line = release.

Figure 4 shows the same data plotted for a particular bar magnet. It is clear that the maximum operate and release distances occur at about 90° and 270°, when the magnet is aligned with the sensitive axis of the sensor. It is also obvious that the operate and release distances span a wide range of angles, but with a deep null when the magnetic field is perpendicular to the long axis of the device package.

Operate and Release Distance vs. Angle (mm)

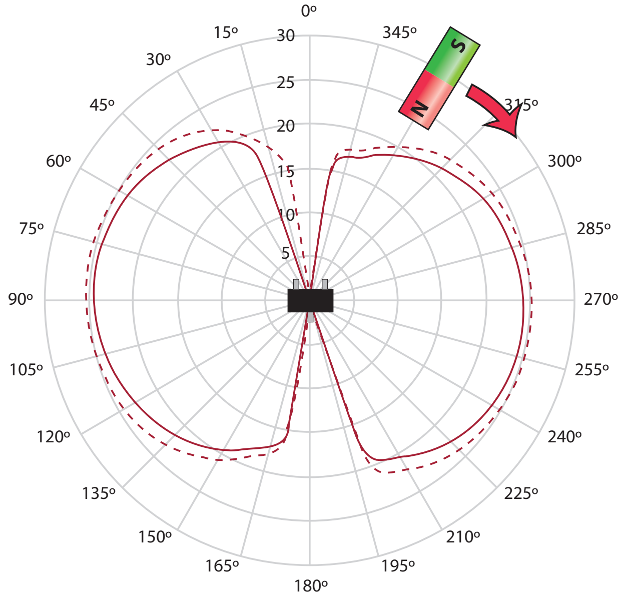


Figure 4: This figure contains the same data as Fig. 3, but plotted as Operate and Release distance in mm, as a bar magnet is rotated around the sensor.

The sensitivity lobes are rotationally symmetric around the sensitive axis of the sensor. Figure 5 shows the operate and release distances plotted in the z-y plane, perpendicular to the top of the package. The same null response at 90° relative to the package is observed. The irregularities in the contours are due to the limited number of points that were sampled.

The operate and release sensitivity lobes shown in this section apply to all RedRock® digital sensors.

Sensitivity vs. Temperature

RedRock® TMR sensors are relatively insensitive to changes in temperature from -40°C to +130°C. Temperature sensitivity graphs are shown in the product data sheets available for download at the Coto Technology website www.cotorelay.com. The graph shown in Figure 6 is typical of an omnipolar part - in this case, with a nominal 30G operate point (B_{OP}).

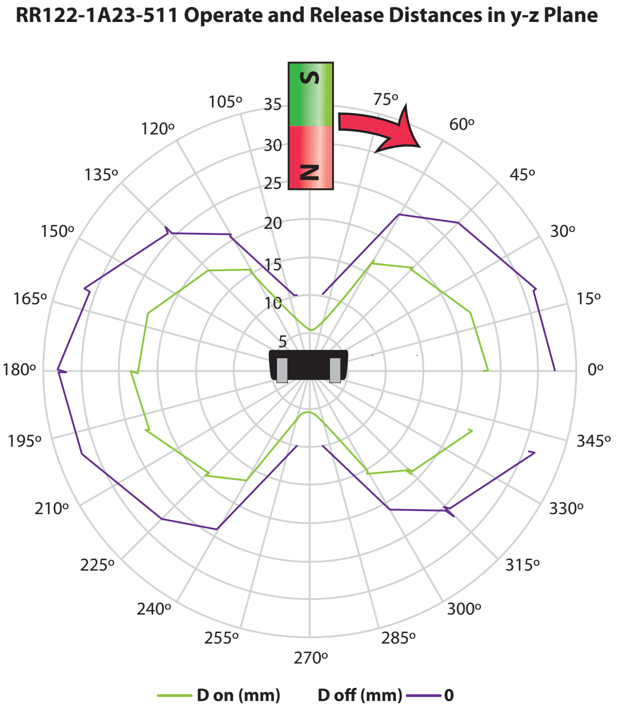


Figure 5: Operate and release distances in y-z plane, perpendicular to the top of the SOT-23 package.

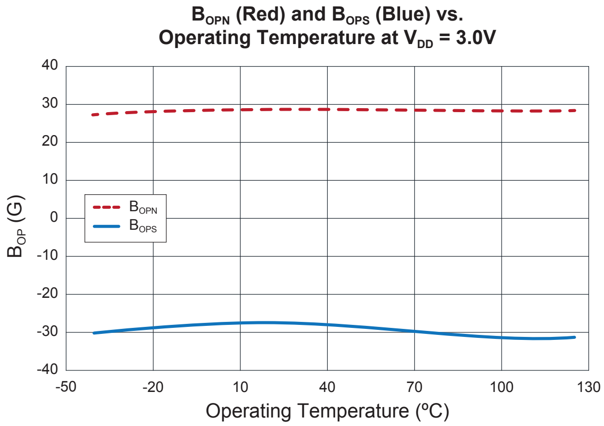


Figure 6: Variation in operate and release points with temperature, omnipolar RedRock® TMR sensor.

Effects of High Magnetic Fields

Generally, RedRock® digital and analog sensors are not damaged by static magnetic fields up to at least 2000G. To avoid exposing sensors to fields greater than 2000G, it is good practice not to bring a permanent magnet closer to a RedRock® sensor than a distance of half the cube root of its volume. For example, a Neodymium magnet shaped as a 10mm cube should not be brought closer than 5mm to a RedRock® sensor. Always consult individual product data sheets for actual part specifications with regard to Maximum Magnetic Field Exposure (B_{MAX}).

MORE INFORMATION

Basic Physics of Tunneling Magnetoresistive Sensors

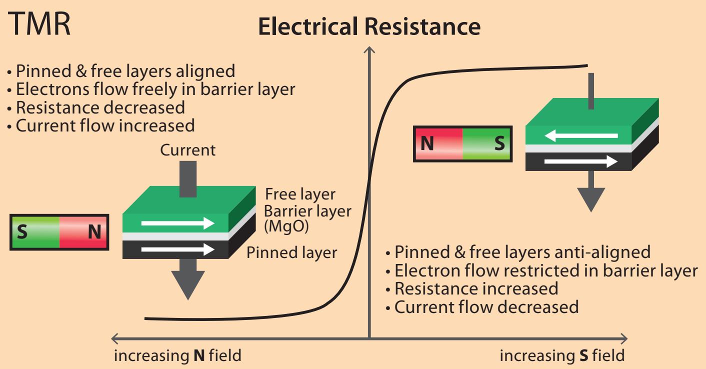
All magnetic sensors measure the magnitude of a magnetic field and, in some cases, its polarity. A TMR sensor is a specific kind of magnetic sensor where a local magnetic field directly regulates the electron flow through the device, causing its electrical resistance to change in accordance with the magnitude of the magnetic field. Hence, the term "magnetoresistive". The term "tunneling" comes from the way that the electron flow is controlled.

TMR is now a well-established magnetic sensing technology used, for example, in most computer hard disk drives. However, the way it works is steeped in quantum theory and late 20th century physics. Most people know that electrons have an electrical charge, but electrons also have a lesser-known property called "spin." Furthermore, as a consequence of the quantum theory of matter, an electron can only have one of two forms of spin, known as "up" or "down." This phenomenon was discovered about a hundred years ago, by German scientists Stern and Gerlach in a classic experiment involving an oven, silver atoms and a non-uniform magnetic field.

Now, recall that a moving – or spinning – charge generates a magnetic field. It's one of the fundamental laws of electromagnetism. So, spinning electrons behave like tiny magnets. But, because their spin is quantized, they behave like tiny bar magnets, with their poles pointing either up or down. Admittedly, this is a simplification. If those electronic magnets are sent into a non-uniform magnetic field, the force on each end is slightly different, and the "up" spinning electrons and the "down" spinning electrons separate into two separate streams which can be visualized on a detector screen. If the spin had been random, a continuous distribution would have been seen on the detector screen. But the splitting into only two streams of up and down spinning electrons was an early confirmation of the quantum theory by Stern and Gerlach.

What has all this to do with TMR magnetic sensing technology? Let's return to that key word "tunneling." In classical physics, an electrical current (read "stream of electrons") is blocked by an electrical insulator such as glass Polytetrafluoroethylene. To get electrons to pass through the insulator, you have to raise their energy to the point where they have enough energy to crest the hill. It's like rolling a boulder over a hill – you have to supply energy to push it up the hill before it can roll down the other side under its own steam and give some of that energy back. But in the strange world of quantum physics, if the insulator is thin enough and you pile up electrons on one side, some of the electrons can tunnel their way through the insulator "hill" without ever being pushed to the top. Almost magically, they appear on the other side. It's like a railway tunnel spontaneously opened up under the hill. It's all to do with not knowing where an electron really is; you only know the probability of where it is – Heisenberg's uncertainty principle – and that there is a finite probability it can appear on the other side of the hill.

Now for the key building block of a TMR sensor. Imagine a very thin insulating layer only a few atoms thick, sandwiched between two thin ferromagnetic electrodes (Figure 7). By "ferromagnetic" we mean a material like iron or nickel-iron alloy that can be magnetized. First, we magnetize both electrodes in the same direction and try to pass a current between them. Electrons with both positive and negative spins can tunnel through the insulating layer, maximizing the possible current. But if the electrodes are magnetized in opposite directions, electrons with spin magnetization that is opposite to the magnetization of the far-side layer cannot tunnel through the insulating layer, and the current drops because fewer electrons can get through.



Note: Layer thickness not to scale

Figure 7: Simplified schematic diagram of TMR sensor

All that remains is to find a way to set up two ferromagnetic electrodes with an insulating layer sandwiched between them, in a way such that the magnetization direction of one layer can be varied relative to the other. To do this, the magnetization direction of one of the layers has to be "pinned" in place, while the other is made of a soft magnetic material that is easily magnetized in any direction. Special thin-film deposition techniques are used to pin one layer. A way of imagining the TMR mechanism is to think of a water tap with a compass needle fastened to the handle. Pull the North seeking pole of the compass needle with the South pole of a magnet and you can turn the handle to open the tap; repel the needle with a North pole and close the tap. However, the "tap" may still leak electrons a little, since the electron flow is not completely blocked when the magnetization of the layers is antiparallel.

The insulation layer is typically crystalline magnesium oxide (MgO) and is only about 10 atoms thick. Because it's so thin, TMR sensors can be prone to damage by electrostatic discharge (ESD), so ESD protection diodes are incorporated by Coto. Also, because the insulating layer is thin, even modest voltages across the TMR device set up high voltage stress gradients, so TMR sensors are operated at relatively low supply voltages in the 1.7 to 5.5V range.

RedRock® TMR Magnetic Sensors by Coto Technology

Offering **ultra-low power consumption, high sensitivity, miniature package size and short lead times,** Coto's RedRock® series of analog and digital TMR magnetic sensors are ideally suited to the demands of next generation security, metering, medical, automotive, instrumentation, and industrial markets. Target applications include fluid level detection, open-close detection, proximity sensing, rotary sensing and any application where the device or product needs to wake up, turn on and perform – thus providing a true "out-of-the-box" experience.

A handy RedRock® TMR magnetic sensor **Selector Guide** can be downloaded from Coto's Website. In addition to providing the primary specifications for each sensor type, the guide provides valuable reference and application information.

Coto's website also provides an extensive **Resource Library** with Application Notes, Videos and Product Datasheets. Content is growing, so check back often. Here are just a few App Notes you might like:

- **How to Pair a Magnetic Sensor with the Right Magnet for a Cost-Effective Solution**
- **Modernizing Security Systems with TMR Magnetic Sensors**
- **Speed and Estimation Detection in Rotating Systems**
- **Magnetic Sensing for Open and Anti-Tamper Detection**

Coto's Application Engineers are readily available to answer questions specific to your device design.

Contact us today for Applications Support. | Samples are available.