Application of magnetic sensors in automation control

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Abstract: Controls in automation need speed and position feedback. The feedback device is often referred to as encoder. Feedback technology includes mechanical, optical, and magnetic, etc. All advance with new inventions and discoveries. Magnetic sensing as a feedback technology offers certain advantages over other technologies like optical one. With new discoveries like GMR (Giant Magneto-Resistance), TMR (Tunneling Magneto-Resistance) becoming feasible for commercialization, more and more applications will be using advanced magnetic sensors in automation. This paper offers a general review on encoder and applications of magnetic sensors in automation control.

1. Overview—control and encoding

In order to achieve motion control, one needs information about the speed and/or the position of the moving or sliding part, which will be referred to as “slider” in linear motor or “rotor” in rotational motion. Such sensing and feedback device, which can be called “encoder” or “tachometer” for speed measurement only, could be purely mechanical. Mechanical signal is generated when a mechanical part touches another one like a mechanical revolution counter or the alarm in a mechanical clock. A device with mechanic contact can generate electric signal when a mechanical part comes in touch with another mechanical part. Shown in Fig. 1 is an example. There is a disk with conductive patterns or pads that are separated by insulating material and a conductive probe or pin. Whenever the disk or the pin rotates to where the pin comes in contact with the conductive pads, a current signal or a pulse can be generated. The signal is feed into a control system, which makes use of the information from the signal to complete certain motion control, either speed control or position control or both. The mechanical feedback device is simple, typically of low resolution but robust and is still being used today in some industry including applications in automobiles. Nevertheless, mechanical feedback devices can’t meet the requirements for many other applications. The technology moves on to optical, electronic and magnetic ones.

In general, an encoder can generate signal to measure position and/or speed, which be classified as relative or absolute encoder. A device that generate signal to measure speed only is usually called tachometer. A relative encoder is also referred to as incremental or quadrature encoder, which generates signal about the relative position of a rotor or slider to a reference point. On the other hand, an absolute
encoder, which is sometimes also called as parallel absolute encoder, generate signal about the absolute position of a rotor or slider.

Fig. 1 Schematics of an encoder with mechanic contact.

What shown in Fig. 1 is actually a tachometer. By measuring the time the pin moves between each pad, one can obtain the speed of the rotor, but not the position of the rotor.

Typically two signal tracks and two sensors are used in a relative encoder as shown in Fig. 2 as a simplest example. The two tracks have signal patterns separated at 90 degree apart (quadrature). If we denote the blank area as “0” and the dark area as “1”, the coding looks like in Table I, while the pulse sequence looks like in Fig. 3 when the disk rotates in the clockwise direction. The coding will look like in Table II if the disk rotates in counter clockwise direction. From the pulse sequence, one can tell whether the rotation is clockwise or counter-clockwise as well as the speed, if time is recorded, but not the position yet. In order to know the position, another signal is needed as a reference for at least once every rotation. However, if a machine stops, the next time when the machine starts, the feedback system can’t tell the machine where the position is until one rotation is completed through the reference point. Note that in this specific example as in Fig. 2, there are only two patterns, blank and dark, in one track. The two sensors can actually generate information about the absolute location of the disk within 90 degree resolution. This coincides with an absolute encoder in this simplest example. If there are more than 2 patterns like blank, dark, blank, dark, etc. on one track, the two sensors can’t generate information about the absolute location of the disk.

Fig. 2 Example of a relative encoder with two sensors and two tracks, rotating in clock wise direction.
In an absolute encoder, usually more than 2 sensors are used and the number of sensors depends on the resolution. The math is simple, resolution = $2^N$, where $N$ is the number of sensors needed. For a simple case when 3 sensors are used, the coding looks like in Table III. Note that there are different ways of coding. The one in Table III is the so-called Gray coding, where two successive values differ in only one bit, which is more error proof than other ways of coding. In this example, there are 3 sensors, so the resolution is 8. This means one can get as accurate as 45 degree since $360/8=45$. Each of the 45 degree area has a unique and therefore absolute code. Compared with the relative encoder, the feedback system made of absolute encoder can always tell a machine where its position is as long as the power is on.

With the introduction completed, we will turn to specific encoder types, optical and magnetic.

### Table I Coding of a relative encoder in Fig. 2 when rotating in clockwise direction.

| A | B |
|---|---|
| 0 | 0 |
| 0 | 1 |
| 1 | 1 |
| 1 | 0 |

### Table II Coding of a relative encoder in Fig. 2 when rotating in counter clockwise direction.

| A | B |
|---|---|
| 0 | 0 |
| 1 | 0 |
| 1 | 1 |
| 0 | 1 |

![Fig. 3 An example of absolute encoder with three tracks and three sensors.](image)
2. Optical encoder

An optical encoder is made of a light source, a disk and a receiver. In a transmitting optical encoder, light pass through open slots on a disk as shown in Fig. 4. In a reflective optical encoder, light gets reflected from a disk back to a receiver on the same side of the light source. In both cases, light intensity changes according to the patterns on the disk.

| Sector Angle | Track 1 | Track 2 | Track 3 |
|--------------|---------|---------|---------|
| 0° to 45°    | 0       | 1       | 1       |
| 45° to 90°   | 0       | 1       | 0       |
| 90° to 135°  | 1       | 1       | 0       |
| 135° to 180° | 1       | 1       | 1       |
| 180° to 225° | 1       | 0       | 1       |
| 225° to 270° | 1       | 0       | 0       |
| 270° to 315° | 0       | 0       | 0       |
| 315° to 360° | 0       | 0       | 1       |

3. Magnetic sensor and encoder

3.1 Hall

Hall sensors have been widely used in motor and control for commutating and encoding. In brush DC motors, currents are directly commutated by brushes. In brushless DC motors, currents are supplied by a drive. There two types of drives, sinusoidal and trapezoidal. In a typical trapezoidal
brushless DC motor, there are three phases that are typically connected in “Y” configuration. Each phase can generates back EMF (Electromotive force) when rotor rotates. The supplied current needs to be on phase with the back EMF in order to generate maximum torque. Typically three magnetic sensors are used to detect the position of the rotor. The information is feed into a drive to trigger current supply into the phases. Most popular sensors for this application are digital Hall sensors. This is shown in Fig. 5.

Fig. 5 Hall signal for commutating and back EMF wave of a typical trapezoid motor.

Most motors have large enough size to accommodate the three Hall sensors. For miniature motors, there are cases that the Hall sensors are too large. People have no choice, but go sensor-less, where the drive can pick up the back EMF signal and trigger current supply accordingly. The sensor-less design has its disadvantages. People use this design mostly because there is no other choice. Other types of magnetic sensors like AMR (Anisotropic Magneto-Resistance), GMR or TMR can be intrinsically made small or even integrated into a circuit, whether they will be used for commutating is an uncharted territory. Factors like the overall package size, package compatibility, and cost need to be considered for this application.

Besides being used in commutation, Hall sensors have been widely used in motor encoding for control. Resolution as high as 14 bits or 16384 per revolution has been claimed. An example is shown in Fig. 6, where 8 halls are evenly spaced around a circumference of a circle with the two pole magnet radially magnetized. When the magnet rotates, the 8 halls pick up signal simultaneously. The position of the magnet is obtained by taking the signal from all the 8 halls into consideration for calculation. Another configuration is to have the Halls sitting underneath the two pole magnet as shown in Fig. 7 with the magnet axially magnetized. These types of encoder are not truly digital one. It extrapolates the information from the Halls to “predict” the position in a digital format. If the magnet is magnetized into multiple poles, with the halls at certain location, it is possible to generate truly digital output. Whether it can achieve high resolution depends on the sensitivity of the sensors and the gap between the sensors and
the magnet. Even though they are not truly digital encoders, they have been widely used in automation, but the accuracy of this type encoder is sensitive, subject to change in temperature, mounting accuracy, etc. Because of this and other factor like cost, these types of encoder have not found wide application in harsh environment like automobiles and others.

![Fig. 6 Schematics of a magnetic encoder with magnet radially magnetized.](image)

**Fig. 6** Schematics of a magnetic encoder with magnet radially magnetized.

![Fig. 7 Schematics of a magnetic encoder with magnet axially magnetized.](image)

**Fig. 7** Schematics of a magnetic encoder with magnet axially magnetized.

### 3.2 AMR

AMR phenomenon\(^2\), the resistance of a magnetic material varying with regard to direction of the magnetization, follows a formula as:

\[
R = R_0 + \Delta R \cos^2 \theta
\]
Where $R_0$ is the resistance when its magnetization is perpendicular to that of the sensing current; $\Delta R$ is the maximum resistance change; $\theta$ is the angle between its magnetization and the orientation of the sensing current. The typical AMR effect is about 2-5%, meaning the resistance of a magnetic material could have a difference of 2-5% of its resistance when its magnetization change with respect to that of the sensing current or $\Delta R/R_0 \approx 2-5\%$. Even though, it is still more sensitive than regular Hall sensors and can be miniaturized.

AMR had not found wide applications until 90’s of last century when hard disk drives made a transition from inductive reading to AMR reading technology. Besides that, AMR has been used in MRAM (Magnetic Radom Access Memory) for niche market applications. There is no report of wide application in motor industry due to factors like necessity, cost, etc. Currently commercial AMR sensors are available from Honeywell, NXP semiconductor, Sensitec. AMR sensors in principle can be used to replace the Halls in all previous examples, but one may need to modify circuits to accommodate difference in signal pattern.

3.3 GMR and TMR

GMR was discovered in 1988 and won the physics Nobel prize in 2007. It has been widely used in disk drive since late 90’s and now starts to be replaced by TMR. The GMR effect comes from spin scattering, where highest resistance is observed when electrons with spin polarized by one magnetic layer move to another magnetic layer of opposite magnetization direction and lowest resistance occurs of the same magnetization direction. The simplest structure is shown in Fig. 7 where two magnetic layers are separated by a metal layer, typically of copper. The resistance formula of this structure is described as

$$R = R_0 + \Delta R \left(1 - \cos \theta\right)/2$$

where $R_0$ is the resistance when the two magnetic layers have its magnetization in parallel; $\Delta R$ is the maximum resistance change; $\theta$ the angle between the magnetization of the two magnetic layers. Typical GMR effect is tens of percent, meaning the resistance of a GMR structure could have a resistance change or $\Delta R/R$ up to tens of percent when the magnetization of the adjacent magnetic layers change direction in relative to each other.

TMR was discovered earlier than GMR, but not been widely used until early this century in disk drive. In a typical TMR structure, the (copper) spacer layer is replaced by an insulating layer like Al$_2$O$_3$, MgO, etc. In TMR, the sensing current pass through all the layers, often called current perpendicular to plane configuration; while in GMR, the sensing current flow in the plane of the layers, often called current in plane configuration. TMR effect could be as large as hundreds of percent.

The most practical structure of GMR or TMR is the co-called spin valve type in Fig. 8, where one of the magnetic layers, the co-called pinned (magnetic) layer, has its magnetization fixed or pinned by an antiferromagnetic layer or synthetic antiferromagnetic layers, at a certain direction and only the magnetization of the other layer, the so-called free (magnetic) layer, reacts to field and change its direction.
Both GMR and TMR have significantly higher sensitivity than Hall sensors. Commercial GMR sensors are available from NVE and Sensitec, but no significant application in motor industry has been reported. In hard disk drives, the tracks are magnetized in either north or south polarity, a true digital format. Currently the linear density in hard drives is over 2000k bpi (bit per inch). This means a bit occupies a length of 12.7 nm or less. If the same linear density can be made feasible in rotary encoder of 10 mm diameter, the resolution would be almost 2.5 millions per revolution and it is truly digital! No encoder can get near to this resolution today, but there are serious challenges to make use of the drive technology in encoders. Still, patents of GMR to be used as an encoding technology have been granted 2-6. Shown in Fig. 9 is one example. In principle, GMR and TMR can be easily miniaturized and integrated into circuits, and should find applications in miniature motor applications if not for large size motor. The possible issues include cost with GMR or TMR sensor being multiple or ten times or more costly than halls; package compatibility; for example, NVE’s GMR sensors have completely different packages from that of the Hall sensors, etc.

One common issue with regard to new magnetic technology like AMR/GMR/TMR is that experts in automation and control may not have much awareness of the new technologies and their superior advantages. For example, these new technologies can offer significantly higher sensitivity, which means the magnets used to produce field to actuate the sensors can be made smaller. This in many applications means low inertia for the rotor or slider, which in turn means higher acceleration, more precision control, etc.

4. Conclusions

In today’s automation and control industry, optical and Hall sensor based magnetic technologies dominate the market, while mechanic still plays some role. But the new magnetic technologies like AMR/GMR/TMR have yet to be widely used in spite of super advantages in sensitivity, temperature stability, etc. due to factors like lack of awareness by experts in automation and control, cost, connection and package compatibility, etc. However, there are some applications, like in miniature motors, high end products that require high accuracy and low inertia, etc., where regular Hall sensors can not be used due to factors like limited space or signal sensitivity, temperature stability, etc. This is where AMR/GMR/TMR can find applications.

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