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Magnetic vs. Optical Engines

What You Should Know When Choosing the Right Encoder Engine for Your Application

Consider factors like resolution, environmental conditions, magnetic noise, and budget when choosing the best sensing technology for your application.

AI25

NorthStar
RIM Tach 8500 NexGen

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Optical vs. Magnetic: How to Pick the Right Encoder Engine

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At the heart of every encoder lies the encoder engine that converts motion into a signal that can be translated by external electronics into speed or position. Most encoders operate based on either optical or magnetic sensing. Each of the two types of encoder engines has its own set of benefits and limitations. In general, optical encoders are good choices for applications requiring high resolution and/or low cost, while magnetic encoders are the best choice for harsh environments. That said, there are no hard and fast rules—certain optical encoders carry a hazardous environment rating suitable for the oil and gas industry, while some magnetic encoders can be quite affordable. Building a successful system requires knowing the options, understanding the pitfalls, and matching the attributes of the encoder engine to the needs of the application.

Optical Encoders

Optical encoder engines typically consist of three main elements: a light source (LED) to generate a beam, a code disk to modulate the beam, and one or more photo-detectors to convert the optical signal into an electrical output. The disk is patterned with alternating transparent and opaque regions that correspond to the output resolution (pulses per revolution) of the encoder. While the LED and photo-detector remain fixed to the encoder structure, the disk turns with the load, introducing a sinusoidal variation in the intensity of the output beam.

Optical encoder engines (as well as magnetic encoder engines) can be implemented as incremental or absolute types, each of which delivers very different performance. An incremental encoder generates a pulse stream that can be converted to displacement, while an absolute encoder outputs a digital word corresponding to a specific angular position of the disk (*see "Incremental and absolute encoders: What's the best solution for your application?")* In an incremental encoder, the disk is patterned in one or more concentric zones, or tracks, each with a radial array of transparent slots (see figure 1); an additional track with a single slot (the Z channel) can be used for indexing or establishing a home position. The disk of an incremental encoder acts like a chopper, converting the input beam to a series of pulses.

The code disk for an absolute encoder features a series of concentric zones, each corresponding to one bit of resolution. The readout sensor includes a separate detector for each bit, and the electronics combine that data into the digital output.

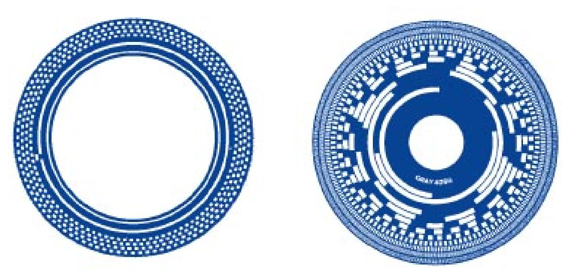

Figure 1: Incremental encoder disk (left) shows slots that modulate the optical beam, and the Z channel, with its single slot, on the inside. Each ring of an absolute encoder code disk (right) corresponds to a different bit of the digital word that encodes location, running from most significant bit (inside) to least significant bit (outside).

Optical Mask Encoders
Optical encoders can be split into mask type and phased-array designs. Of the two, optical mask encoders are the most basic. They typically utilize discrete photo-detectors along with a mask or grating. The mask, which is placed over the photo-detector, features an arc of slots the same size as the slots on the disk, one arc for each track (see figure 2). Because the slots on the mask are the same size as those on the disk, they prevent spillover between channels.

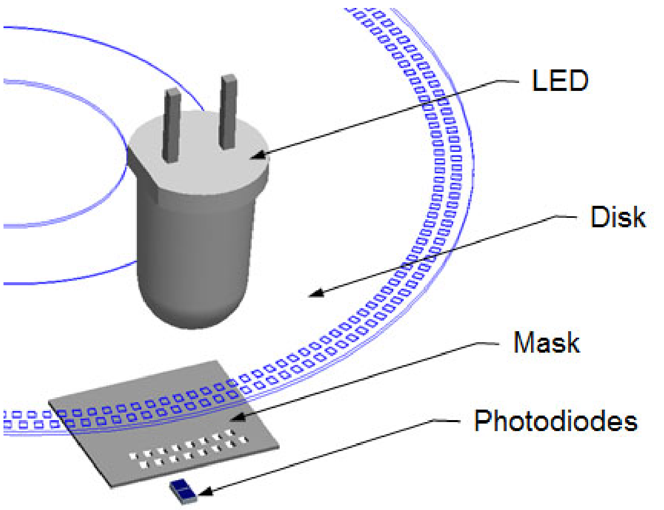

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Figure 2: In an optical mask encoder, the patterned disk, which turns with the load, passes between a fixed LED and a photosensor. As the disk turns, the alternating transparent and opaque regions modulate the LED beam. The slots on the mask, which correspond to those on the disk, help prevent crosstalk between channels.

The advantage of mask-type optical encoders is that they allow greater flexibility to offer a variety of output resolutions (PPR). Only the disk and mask require customization for a specific PPR; the same photo-detector array can be used for all the resolutions.

The trade-off is that higher resolutions require a very tight air gap between the disk and the mask/photo-detector assembly. The air gap can be in the range of 40 to 80 µm (0.0015 to 0.003”). These air gaps require tight manufacturing tolerances for disk flatness and alignment and can place limitations on the durability of the encoder in harsh environments (see disk material considerations, below).

Incremental encoders are available in single-channel (A channel) and quadrature (A channel and B channel) versions. Although single-channel encoders are useful for tracking counts and displacement, they cannot determine direction. Detecting direction of motion requires a quadrature design, in which the B channel is 90° out of phase (in quadrature) with the A channel. The most common way to implement a quadrature encoder is to pattern the disc with a separate track and detector for each channel. The problem is that for high-resolution designs, the detectors tend to be wide compared to the slots, introducing crosstalk. A mask can be used to prevent this.

Another way to implement a quadrature encoder is to use a simple, single-track disk for all channels and use the tracks on the mask to introduce the 90° phase shift between channels. A mask can also help compensate for thermal variation by defining a complementary channel that is 180° out of phase with the primary signal—for example, A and A’. This makes it easy to remove common-mode signal variation. In both cases, the mask reduces disk complexity and increases manufacturing tolerances.

Optical Phased-array Encoders
Phased-array optical encoders provide an effective alternative to overcome the limitations of the mask-type optical encoder. Instead of capturing data with a single discrete detector per channel or per bit, a phased-array optical encoder uses an array of detectors integrated into an application-specific integrated circuit (ASIC; see figure 3). This design allows the optical signal to be averaged over a large number of detectors for each channel, compensating for signal variation introduced by misalignment, disk eccentricity, and other error sources. As result, phased-array encoders can be built with air gaps an order of magnitude larger than their conventional counterparts. Manufacturers no longer have to resort to ultraprecise (and expensive) machining or time-consuming techniques like shimming to produce a device that works properly. At the same time, reliability and performance are designed in, while the economies of scale provided by batch processing keep pricing reasonable.

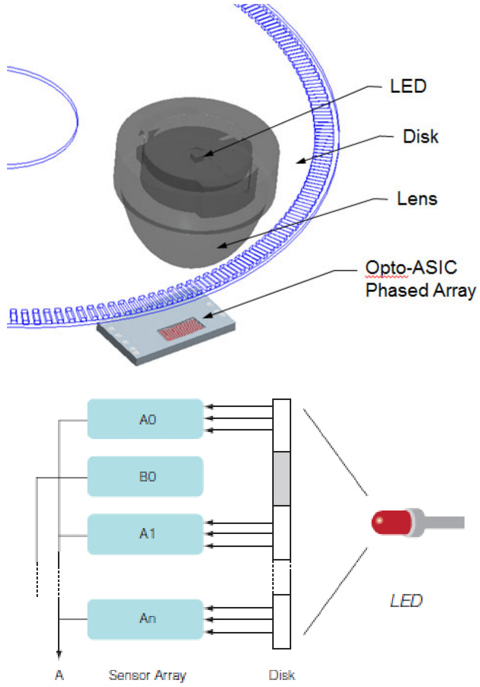

Figure 3: An optical phased-array encoder (top) uses a solid-state detector array to average out signal capture over multiple detectors (bottom) to increase sensitivity and reduce error.

The resultant device is automatically aligned and inherently more robust than discrete versions—phased-array encoders such as Dynapar's **HS35R** can tolerate shock loads as high as 400 g's. Unlike discrete detectors, which are comparatively wide with respect to the slot width, the detectors in a phased-array encoder are about the same size as the slots, eliminating the need for a mask. In addition, the devices no longer need PCB components like potentiometers, presenting less complex, more deterministic designs with fewer points of failure.

Code Disk Material Considerations

Encoder code disks can be made of metal substrates with slots corresponding to the transparent regions. This approach is useful for applications with high shock load and vibration, but mechanical considerations limit the resolution—a metal disk with too many slots will be too fragile to survive. More commonly, for higher-resolution options, encoders use disks with glass substrates that have opaque zones defined by lithographically patterned metal films. The rigid glass disks allow a very narrow air gap between disk and detector, which limits beam spread and increases resolution. The downside of glass disks is that they can shatter. Mylar offers a less fragile alternative, although the disks can sag if not properly mounted and can even flutter when rotating at very high speeds. As a result, they require a wider air gap than glass, which reduces resolution.

Optical encoders tend to be the first-choice solution for a variety of applications ranging from elevators to medical devices. Typical incremental systems can deliver resolutions as high as 5,000 PPR at an economical price point. For highly demanding applications, some incremental encoders can achieve 10,000 PPR direct read, while absolute encoders can achieve resolution as high as 18 or 20 bit (which corresponds to as much as 1×10^6 PPR), although the trade-off for this performance is higher cost and complexity. The optical beam is also immune to extreme magnetic fields such as those seen with MRI machines or DC brakes. Finally, phased-array optical encoders can easily tolerate heavy shock and vibration environments, making the technology a good fit for oil rigs, heavy vehicles, and military systems.

No solution is perfect, however. With temperature variation and age, LED output intensity tends to drop, which can compromise the signal, potentially causing the encoder to miss counts. The rate of degradation depends on the level of current used to drive the LED. It can be a particular problem in the case of high-resolution encoders, which require high drive currents to generate a sufficiently intense optical signal to pass through the very fine apertures of the code disk.

Like any other optical system, optical encoders are vulnerable to environmental contamination. Dust and moisture can cause scattering, while films of oil or other chemicals found in industrial environments can contaminate optical surfaces and attenuate signals. Devices can be sealed to limit the incursion of solids and liquids, of course—for an application like CNC machining or metal processing, the best solution might be an IP-rated optical encoder (see "Understanding encoder IP ratings").

What to know before you choose:

1. What is the environment? Will the encoder be exposed to dust or liquid?
2. What kind of resolution does the application require?
3. Does it involve shock or vibration? If so, how much and how frequently?
4. Will the system be exposed to strong magnetic fields or electronic noise?
5. What is the budget?
6. What are the lifetime and duty cycle requirements?

Magnetic encoders
Although optical encoder engines offer many advantages, for some applications, only a magnetic encoder will do. Magnetic encoder engines operate by detecting perturbations to a magnetic field caused by movement of a ferromagnetic material attached to the load. They are available in incremental and absolute designs. In the simplest version, a toothed metal gear serves the purpose of the optical code disk, with the resolution driven by the number of teeth per revolution. Alternatively, this can be a rotary drum (wheel) that is magnetized around its circumference with alternating north and south poles. These alternating domains function like the slots in an incremental optical encoder disk (see figure 4).

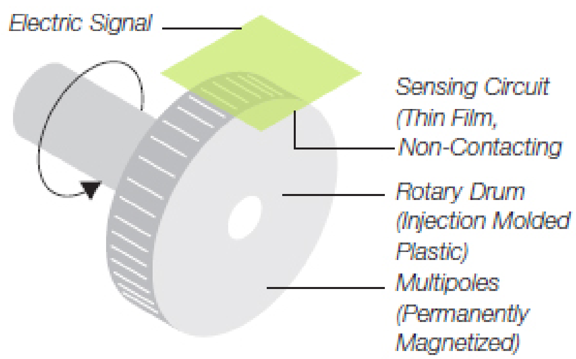

Figure 4: Magnetic encoders feature either a toothed ferromagnetic disk or a drum (wheel) that features alternating magnetic field about the circumference.

The simplest magnetic detector is a variable-reluctance rotary sensor, or magnetic pickup, which consists of a permanent magnet wound with a coil. When the ferromagnetic gear tooth moves past the coil, the changing magnetic field generates a voltage pulse; the electronics then convert the signal to speed. In general, variable-reluctance sensors work best at higher speeds (180 inches per second or better). Because the number of pulses per rotation generated by the devices is directly related to the size of the gear teeth, practical issues like machining and mechanical strength limit the resolution of typical models to around 120 PPR. The technology can achieve 240 PPR, but only with very tight air gaps, which increases complexity and cost. As a result, OEMs seek other options whenever possible.

Magnetoresistive encoders provide a more sophisticated alternative. A magnetoresistive sensor consists of a resistor formed of a magnetically sensitive alloy such as nickel iron (NiFe). An external magnetic field stresses the magnetic domains in the NiFe, reducing the resistance of the material. When the field is removed, the resistance normalizes rapidly, making it a useful tool for sensing magnetic fields in applications like hard-disk-drive readout.

A magnetoresistive encoder consists of an array of lithographically patterned thin-film resistors fixed to the housing and a drum with alternating magnetic domains attached to the motor shaft (see figure 5). As the domains pass by the sensor array, the output resistance changes, which produces a sinusoidal signal. Magnetoresistive encoders can achieve resolutions several times as high as for variable-reluctance encoders and sensor-to-drum separations an order of magnitude greater. Because the encoders are essentially solid-state devices, they are both economical and robust.

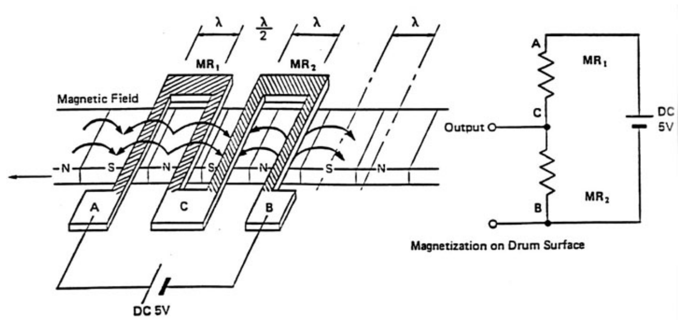

Figure 5: In a magnetoresistive encoder, magnetic domains passing by thin-film resistors modify the resistance to generate a sinusoidal signal.

The technology does have drawbacks. Although fabricated using semiconductor technology, magnetoresistive sensors are not solid-state devices, so they cannot be integrated directly with the processor at the chip level. As discrete sensors, they're larger and more difficult to fabricate, and require additional support circuitry. That adds both cost and complexity.

Hall-effect encoders
The alternative is a Hall-effect sensor, a solid-state detector based on the Lorentz force. A Hall-effect sensor consists of a layer of semiconductor material, typically p-type, connected to a power supply. An applied magnetic field exerts a force on the charge carriers, causing them to separate to create a potential difference. In practical terms, when a magnetic domain on the drum passes by a Hall-effect sensor, the interaction generates a voltage spike. The amplitude and frequency of the magnetic perturbation can be analyzed to determine speed and displacement.

Although discrete Hall-effect sensors can be useful—for example, detecting when a laptop is closed in order to put the machine into standby mode—they have drawbacks. Their size limits resolution. They have to be assembled and aligned using pick-and-place techniques, which makes them more difficult and more expensive to manufacture, as well as more vulnerable to shock and vibration. Encoders based on Hall-effect array sensors provide a better solution.

Fabricated using semiconductor techniques, Hall-effect array sensors integrate both sensor and processor in the same chip for a robust, compact, easily manufacturable component (see figure 6). As with phased-array optical encoders, the designs spread data capture across multiple detectors, averaging out errors and increasing sensitivity.

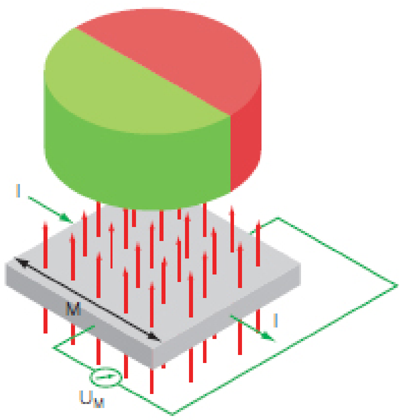

Figure 6: A Hall-array sensor averages the signal over multiple detectors to deliver robust, high-resolution performance that is insensitive to misalignment, shock, and vibration.

Magnetic encoders can be extraordinarily robust. Because magnetic encoders are based on an inductive effect, they do not require bearings, which removes a point of failure from the system. Typically, the electronics are encapsulated so that they are not exposed to the elements. As a result, the devices can operate covered in dust in a sawmill or splashed daily in a washdown environment without any special protection (see figure 7). Temperature extremes do not affect their performance, making them a good fit for the punishing conditions found in industrial applications like paper manufacturing and glass fabrication. They can tolerate levels of shock and vibration that even optical phased-array encoders could not survive, and their performance does not degrade with age.

Figure 7: Magnetic encoders operate effectively even when covered with dust and oil.

Common wisdom holds that optical encoders are cheaper than magnetic designs, but that's not necessarily the case. Depending on conditions, an IP-rated optical encoder may actually prove more expensive than a magnetic solution in the long run. It's also important to note that while magnetic encoders cannot achieve the higher resolutions available from optical engines, they don't necessarily always need to—1024 or 2048 PPR will work quite nicely for a paper machine, for example. Meanwhile, today's magnetic devices can still achieve resolutions as high as 2048 PPR, in the case of Dynapar's incremental **RIM Tach 8500 Nex Gen,** or 16 bits, in the case of the **AR62 absolute series.** Along with that performance, the RIM Tach boasts a whopping 0.08-in. airgap, which is several times larger than possible with even the best optical encoder.

There is no one perfect solution, of course, only the best solution for a given project. Applications involving high levels of magnetic interference can be a problem, although that can be mitigated with shielding, such as the ductile cast-iron housing used on the RIM Tach. Ultimately, high magnetic fields are not impossible for these devices but should be taken into consideration during selection and design.

In Summary

One of the most common mistakes in specifying encoders is to let short-term cost concerns drive the decision. After all, a motion system is only as good as its feedback. It's important to remember that the overall outlay for a system includes cost of operations, and not just bill of materials. Choosing a cheap encoder that fails quickly doesn't just cost more in parts but in lost production due to downtime. By keeping in mind the strengths and limitations of the different solutions, OEMs can arrive at the optimal balance of performance, lifetime, and cost.

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