Everything You Should Know About Functional Safety Encoders

How to choose the right encoder for your application.

Functional safety encoders are a crucial part of system safety. (Source: Sensata.)

One of the key factors of any automated system is safety. To ensure safety of operators, machines must operate within safety parameters. If a machine strays from these parameters, safety components should prevent further operation and return the machine to a safe state.

In this article, we'll look at an important component of safe automation: the functional safety encoder. Functional safety encoders monitor a machine's operation and provide feedback if operation conditions reach a predefined unsafe state. Encoder manufacturers provide a wide range of encoders adapted for various applications. To select a proper encoder that will provide effective feedback, designers must analyze the application and operating conditions.

Introduction to Encoders

An encoder is a sensor that converts the motion of a tracked machine to an electrical signal (analog or digital) that is readable by the control device (e.g. counter, PLC). An encoder must provide quality data to enable a clear feedback signal. The signal from the encoder is used to determine count, speed, position or direction of machine operation. The control device, depending on the feedback signal, sends a command to the machine. The encoder is usually one part of a complex automated system which contains components such as motors, drives, amplifiers, brakes and more.

Commonly used encoder types include optical, magnetic and inductive encoders.

Optical Encoders

Optical encoders provide the highest resolution. They are suitable for precise scientific or demanding industrial applications where high precision is required for tracking angular position (fractions of degrees).

The main parts of an optical encoder are a patterned glass code disc and source-detector pair. The code disc is attached to the motor shaft and passes between the source (LED) and photodetector, which are fixed to the frame of the encoder. The code disc is patterned with opaque lines and it moves with the load. The LED emits a beam of light that passes through the disc or is interrupted by the lines as the disc rotates with the encoder shaft. Thus a pulse signal is created and picked up by the photodetector. This signal is converted to speed or position and sent to the controller.

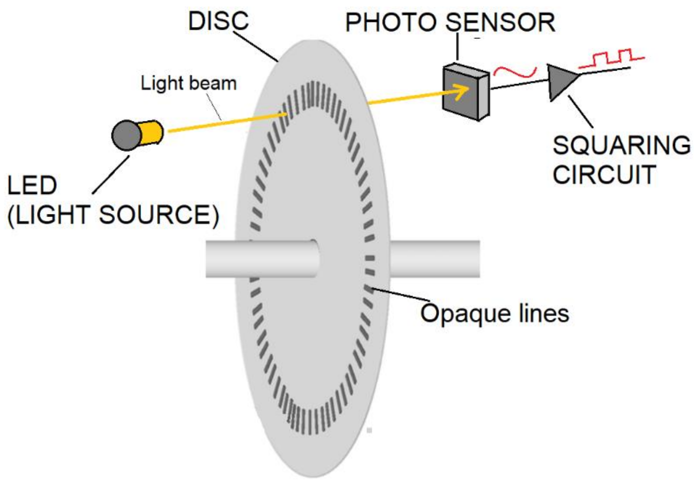


Diagram of an optical encoder.

Optical encoders are sensitive to contamination such as dust and moisture. Since a glass code disc is vulnerable to mechanical shocks, these days it is more popular to use mylar code discs.

Magentic Encoders

Magnetic encoders use magneto-resistive detectors or Hall-effect sensors to detect a varying magnetic field. These encoders use different structures to change the magnetic field, such as a toothed ferrous metal gear and discs patterned with alternating magnetic domains.

Magnetic encoders are suitable for operating in harsh environments and are not affected by water, dust or vibration. However, they are sensitive to high magnetic fields and sometimes require shielding. Magnetic encoders with Hall-effect sensors are a suitable solution for applications in very dirty environments.

Inductive Encoders

In the past, inductive encoders used resolvers containing differential transformers and robust readout coils. The transformers determined the absolute angular position of a rotating load by measuring the induced voltages on the coils. The primary coil was energized and attached to the rotor, while the secondary coils were attached to the stator. The primary coil rotation induced a current in the secondary coils, which was used to calculate the angles.

Modern inductive encoders use a solid-state implementation of a resolver. The coils are flat elements lithographically patterned onto a PCB. Three coils are placed on the PCB and mounted to the stator. The coils are excited by a conductive disk (several µm thick) mounted to the rotor. Inductive encoders provide very high resolution and are resistant to contamination, humidity, temperature and vibration.

The main challenge for inductive encoders is the conductive disc which should be properly selected for a certain application. For example, high-temperature applications should not use soft iron discs, nor should unshielded ferrite code discs be used in high magnetic fields.

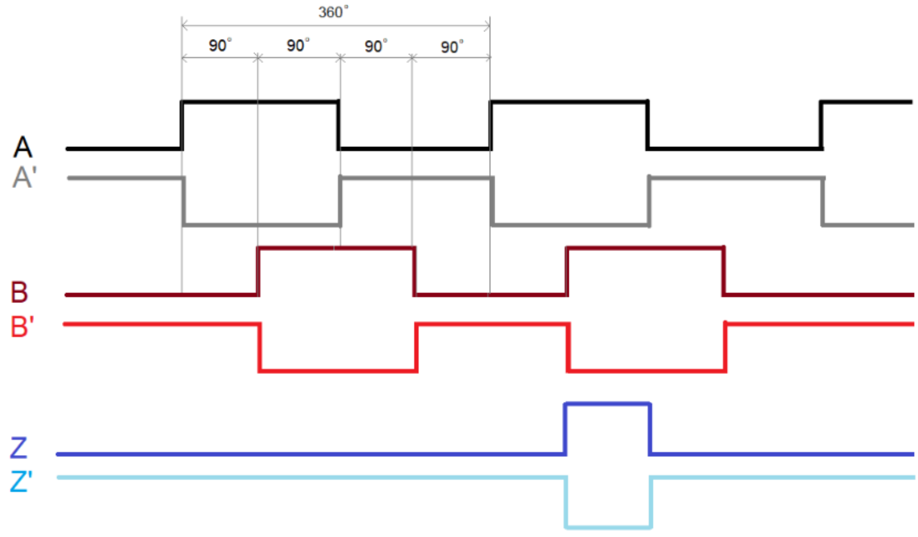
Incremental and Absolute Encoders

Encoders can be incremental or absolute.

Incremental rotary encoders send a signal to the controller for each movement of the shaft. The encoder resolution is defined as the number of signals per one turn. These encoders can determine both position and velocity—the position is calculated by the number of signals in relation to the starting point, and the velocity is calculated by dividing the number of signals by the measured time interval.

Incremental encoders can provide a different number of output signals. A code disc with only one output channel is sufficient when the encoder tracks only unidirectional rotation or speed. The problem with a single channel is that the pulse stream is the same when the disc is rotating clockwise or counterclockwise. This can be used for the application where the rotation direction is not of interest.

Tracking the direction of the rotation requires a quadrature encoder. These encoders use two output signals A and B set up with a 90° offset. Depending on the rotation direction, one signal will be 90° ahead of the other. The encoder output can also involve a third signal Z as an accurate reference point, which typically rises for 90° once every rotation. Encoders can also have differential signals A', B' and Z' which are inverted original signals. Those are control signals that the controller uses to check that there is no error during the transmission. Below is a typical pulse diagram of incremental encoders using these output signals.



Typical output signals from a quadrature encoder. One cycle (period) is 360°, one pulse is 180° and one count is 90°.

Incremental encoders monitor incremental advances according to the initial reference position, which is set at start up. Because of this, they must be re-homed (come back to a reference point) when they are restarted after a shutdown or faulty state. Battery backups can be used to eliminate the need for re-homing after the restart. Incremental encoders are practical and economical for simple applications with a speed control function, such as in a package handling facility.

In absolute encoders, each angular position has a unique digital binary code (Gray code is usually used). This enables the advantage of non-volatile memory, which means that absolute encoders do not lose position information when the power is off. Thus, they are a good solution for applications where re-homing could cause damage or unsafe conditions, such as surgical robots or automotive robots. Absolute encoders are also immune to electrical noise.

Absolute encoders can be single-turn or multi-turn encoders. Single-turn encoders can read position within a single turn of the encoder shaft, which makes them useful for short travel situations. Multiple-turn encoders are convenient for complex or longer positioning situations.

Functional Safety Encoders

Functional safety	IEC 61508
	IEC 62061
	ISO 13849-1
	IEC 61800-5-2

Functional safety regulations as seen in a safety encoder datasheet. (Source: Sensata)

There are several standards that define functional safety and specify requirements for machine design to enable safe operation. To provide reliable feedback, safety encoders must comply with the key functional safety standards:

- **IEC 61508:** Core functional safety standard applied to all critical safety electrical, electronic and programmable systems. This standard defines the Safety Integrity Level (SIL) safety rating framework.
- **IEC 61800-5-2:** Encoders that comply with this standard can be used for safe motor feedback. The standard defines safety-rated drive functions and explains adjustable speed electrical power drive systems, safety requirements and functionality.
- **IEC 62061:** Explains the safety of machinery and functional safety based on EN 61508.
- **ISO 13849:** Defines the safety of machinery and safety-related parts of control systems. It defines the Performance Level (PL) safety rating framework.

Encoders rated at SIL 3 (PLe) provide safe operation in set-up, production and maintenance to significantly reduce operational risks. Examples of SIL 3 (PLe) incremental encoders are the Sensata | BEI models DSO5H, DSU9H, and DSM5.

Specifications and Features of Functional Encoders

When evaluating encoders, be sure to consider the following specifications and features.

Pulses Per Revolution (PPR)

Pulses per revolution (PPR) is the number of pulses that an encoder outputs per revolution, and this determines the encoder resolution. This is equivalent to the number of lines patterned on the code disc. Using this parameter, it is possible to calculate the angle between each pulse. This angle is smaller if the PPR is higher. Usually, the PPR is fixed for an incremental encoder, but programmable encoders enable the PPR to be adjusted by software.

There are many different encoder resolutions. Advanced encoders, such as the Sensata | BEI DSO5H and DSM5, can provide up to 2,500 PPR.

Frequency Response

Frequency response is the maximum encoder output frequency. Encoder operating frequency is provided by the manufacturer and is typically in the range of kilohertz to megahertz. For encoders with 2,500 PPR rotating at 6,000 RPM, the frequency response is 250 kHz (2,500 x 6,000/60).

Encoder manufacturers usually provide information about permissible max speed and continuous max speed. For example, the Sensata | BEI DSM5 shafted mounting (solid shaft) encoder permits a max speed of 9,000 RPM and a continuous max speed of 6,000 RPM, and the Sensata DSO5H hollow shaft encoder has a max speed of 9,000 RPM (permissible) and 6,000 RPM (continuous). When an application requires a high-resolution output for a high-speed system, encoders with a higher operating frequency should be used.

Wiring

To provide system control and safety, encoder data must be sent to the read-out (control) device. For incremental encoders, each channel must be wired directly to the control device. Commonly used wiring approaches are single-ended wiring and differential wiring.

Single-ended wiring uses one wire per each channel connected to the control device and wires for Vcc (Voltage Common Collector) and GND (ground). This is an economical and simple wiring solution, but vulnerable to noise. It can be used for applications with short cables and in low noise environments.

Differential wiring uses two twisted wires for each channel and Vcc and GND wires. It is suitable for noise cancellation and thus for high noise and long cable applications. However, more wires increase the cost and complexity.

Output Drivers

Incremental encoders use output drivers to transmit to the readout device. The controller voltage should be high enough to provide a reliable readout and the signal must be strong enough to be transmitted across the network without interference. Output drivers amplify and process raw signals from the encoder into square-wave signals suitable for transmission to the readout device. Output drivers must be compatible with the other components of the circuit to avoid damage. Modern encoders have the option of digital HTL or TTL operation as an alternative to the sine/cosine outputs found on older functional safety encoders. They support digital TTL/RS422, HTL or sine/cosine 1Vpp outputs.

High transistor logic (HTL) is used for push-pull output drivers. The push-pull driver acts as both a sourcing and a sinking driver and is compatible with both sinking and sourcing controllers.

Although they have a high price, their advantages are maximum flexibility and maximum transmission distance. They drive the encoder to generate output with the same voltage as the input. Typical encoder operating voltage is 11 – 30 V and current up to 250 mA. HTL is flexible to the input voltage value and suitable for applications with variable input voltage.

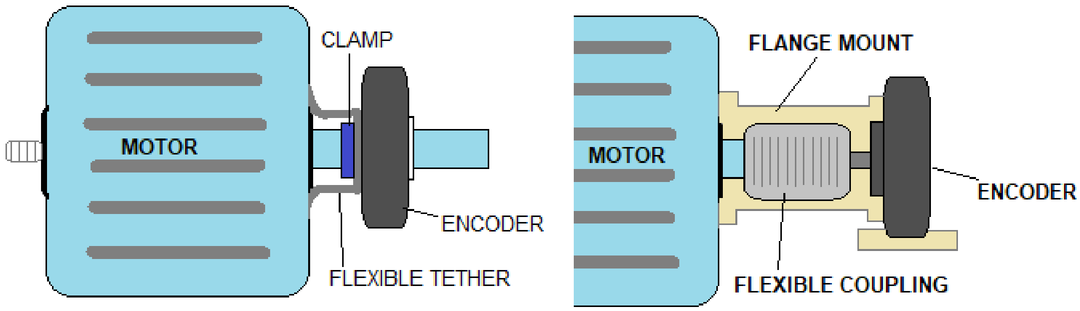
Transistor-to-transistor logic (TTL) circuits provide the output with a constant voltage (5 V) that is not dependent on the supply input voltage. TTL circuits use differential signals that comply with the RS422 signaling standard, which is suitable for noisy environments.

Differential outputs have the best noise immunity and the highest frequency response capability. There are two options for the supply DC voltage range, 4.75 – 5.5 V and 8 – 30 V, providing users flexibility to select a range of input voltages. For example, the Sensata | BEI DSO5H, DSU9H, and DSM5 encoders provide both options. However, TTL output drivers are very sensitive to the input voltage value. A slightly lower input voltage will cause an undervoltage condition in the encoder.

Mechanical Requirements

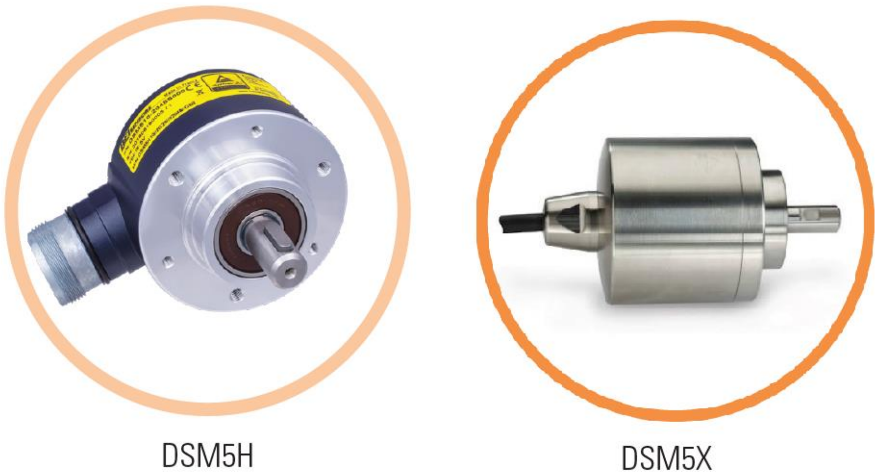
Encoders must be mechanically connected to the tracked system. Since encoders can be used in many different applications, there are multiple options available. Before encoder installation, users must consider available space, form and shape, and the mechanical performance of the shaft.

Encoder manufacturers usually offer different mounting options to provide reliable installation in various applications. Encoder mounting can be classified as solid shaft and hollow shaft. Solid shaft encoders use face-mounting flanges, servo flanges and square flanges, while hollow shaft encoders use tethers.



Hollow shaft encoder installation (left) and solid shaft encoder installation (right).

Solid shaft encoders are connected to the motor shaft or load. Couplings are used to reduce the wear of the bearings because they compensate for the wearing out of the motor shaft. However, couplings can influence the encoder accuracy. This is compensated for with high accuracy encoders such as the Sensata | BEI DSM5 encoder. Additionally, the shaft creates the current path through the encoder bearing and into the electronics.



Examples of solid shaft encoders: the Sensata | BEI DSM5H (left) and DSM5X (right), which is a stainless steel version that is IP69K sealed for washdown applications. (Source: Sensata).

Hollow shaft encoders bypass this shortcoming because the encoder shaft is not coupled to the motor shaft and the current cannot flow through the encoder bearing. Since they are compact, adjustable and versatile, their installation is simple. A hollow shaft encoder is mounted and clamped over the motor shaft. The flexible tether is used to keep the encoder fixed in place and also absorbs shocks and vibration. Because of its reliable performance, hollow shaft encoders are ideal for industrial applications where speed is crucial information.

Example of a hollow shaft encoder, the Sensata | BEI DSO5H. The hollow shaft mounting can accept shafts of 14 mm in diameter. It is mounted with a stator coupling kit and a clamp to secure it to the shaft. (Source: Sensata)

Since encoders operate in demanding environments, it is crucial that they are properly installed to avoid maintenance and operation issues. Designers must predict if the encoder mounting requires additional accessories to make a reliable connection. Quality encoders will provide effective feedback when they are properly selected according to the application and operating conditions. To select the right encoder, it is important to collect as much information as possible about the application and environmental conditions, such as:

- environmental conditions including operation temperature, moisture, mechanical vibration, contamination, etc.
- motion characteristics including type of motion and motion magnitude.
- mechanical characteristics of the machine to determine encoder mounting.
- electrical requirements of drivers and control devices.

To learn more about the functional safety encoders discussed in this article, see the Sensata | BEI solid shaft DSM encoders, hollow shaft DSO encoders, and hollow shaft DSU encoders with optional reduction sleeves for mounting on smaller diameter shafts.