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OnAxis™ encoder technology

Robust OnAxis™ sensor technology is now used as standard in many high volume applications to provide reliable position and speed information. The simple non-contact design makes this encoder technology low cost both in terms of purchase price and reliability. The take up of this relatively new technology is rapidly expanding as designers integrate it into current production models. Application areas are extensive and include automotive power steering, flow control and factory automation.

Although many of the basic principles described for optical encoders can also be applied to magnetic encoders, other specific technical aspects must be understood before using these devices; an important one being that the resolution and accuracy offered is only to tenths of a degree. However, for many applications this is sufficient as only basic positional information is required.

The main benefits of this type of encoder are

- High temperature operation often from –40 °C to +125 °C
- High speed – up to 60,000 rpm
- Non-contact, robust design
- Absolute as well as incremental position data
- Compact low profile design
- Low cost

The OnAxis™ system consists of a chip containing the sensor array and a separate diametrically polarized magnet. As the magnet rotates, the sensors within the silicon pick up on the magnetic flux density (B) and further electronics within the chip produce position information.

Figure 1: OnAxis™ encoder, consisting of a magnet and a chip containing sensors and evaluating electronics.

Almost all encoders regardless of operating principle, initially work from sine and cosine signals. Optical encoders produce up to several thousand periods of sinusoidal signals per revolution, whilst on axis magnetic encoders using Hall sensors produce only one period per revolution. The position within one revolution can be calculated with the inverse tangent function of the ratio between the sine and cosine signals. When calculating the position from the ratio of signals the amplitude is eliminated. The calculation is done with a fast hardware inverse tangent calculator called an interpolator.

$$\varphi = ArcTan\left(\frac{\sin(\varphi)}{\cos(\varphi)}\right)$$

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The sensors in the encoder must produce accurate sine and cosine signals when the magnet is rotating to be able to measure the angular position of the magnet.

Types of magnetic sensing technology

There are two main types of magnetic sensors Magneto Resistive and Hall.

Magneto Resistive sensors:

- provide two periods of sinusoidal signals per revolution. This makes them unsuitable for calculating the absolute position over 360°.
- are only sensitive to the parallel component of B. The sensors are placed in the axis of magnet rotation where the parallel component of B is at its maximum.
- do not have bipolar magnetic sensitivity.
- are non-linear and have electrical hysteresis.
- are sensitive to stray magnetic fields.

Hall sensors:

- provide one period of sinusoidal signals per revolution. The absolute position over 360° can therefore be calculated.
- are sensitive only to the perpendicular component of B. Sensors must be placed out of the magnet axis as the maximum perpendicular component of B is approximately on the magnet edge.
- have bipolar magnetic sensitivity.
- have a linear response to B and do not have electrical hysteresis.
- with differential reading from the sensors, any effect of stray magnetic fields can be reduced.

Although both of these technologies have their own advantages and disadvantages, Hall sensors are often chosen for on axis sensor designs as they have the distinct advantage of being able to provide absolute position data over one rotation.

Hall sensor array

The sensors are arranged in a circle with equal angles between them. A minimum of four sensors must be used or a multiple of four. Sensors are divided in to four quadrants. Each quadrant has the same number of sensors and produces 4 signals which can be marked as S1, S2, S3 and S4 (see *Figure 2*).

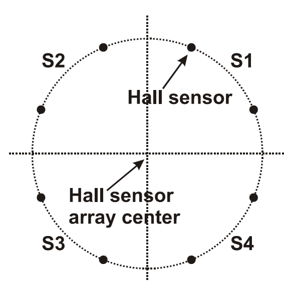

Figure 2: Hall sensor array with four quadrant signals

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The radius of the circle should be in the range of the magnet radius. The four signals are phase shifted by 90° with respect to each other. With proper summation of the signals it is possible to produce a sine and cosine signal as follows:

Sine = S1 + S2 - S3 - S4 Cosine = S1 - S2 - S3 + S4

Opposite signals are subtracted to double the signal amplitude and to eliminate stray magnetic fields.

Magnet materials

Permanent magnets are normally made of strong rare-earth materials such as SmCo or NdFeB. Strong magnetic materials are needed to provide as much magnetic field modulation as possible to exceed stray magnetic fields caused by other magnets or coils near the encoder.

NdFeB material is cheaper than SmCo but it has some disadvantages that must be considered when choosing a magnet for use with magnetic encoders.

NdFeB:

- typical material remanence is 1.2 T.
- the material is corrosive because it contains iron, therefore the magnets must be protected against corrosion.
- maximum operating temperature is around 150 °C. If the material is exposed to higher temperatures it can be demagnetized.
- high temperature coefficient of B (-0.11% / K).

SmCo:

- typical material remanence is 1 T.
- material is non corrosive.
- maximum operating temperature is around 300 °C.
- lower temperature coefficient of B (-0.032% / K).

Magnet shape

The rotating magnet must produce a sinusoidal modulation of B at the location of the sensors. The diametrically polarized and cylindrical shaped magnet satisfies this requirement. For good sinusoidal distribution of the magnetic flux density it is important that the shape of the magnet is cylindrical.

Magnet dimensions

The magnet dimensions must be such to provide appropriate modulation of B at the location of the sensors. Larger magnets provide better performance but they are more expensive. A good compromise between the price and performance is a magnet with a diameter of 4 mm and a height of 4 mm.

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Quality of the magnet magnetization

Magnets should have a North and South magnetic pole of equal size and the magnetic border should be exactly in the middle of the magnet. The difference between the poles is reflected in magnetic offset at each sensor when the magnet is rotating. The offset of the magnetic flux density when the magnet is rotating is an indicator of the magnet's quality. For better accuracy performance the magnets with large offset should be eliminated.

Typical performance obtained from a magnet

Properties are described below for a cylindrical SmCo magnet with a diameter of 4 mm and a height of 4 mm rotating. Only the perpendicular component (B_n) of the magnetic flux density will be described as Hall sensors only detect this component.

The amplitude of magnetic modulation B_n changes with the radius as seen in *Figure 3*. The distance between the sensor and the top of the magnet is 2 mm.

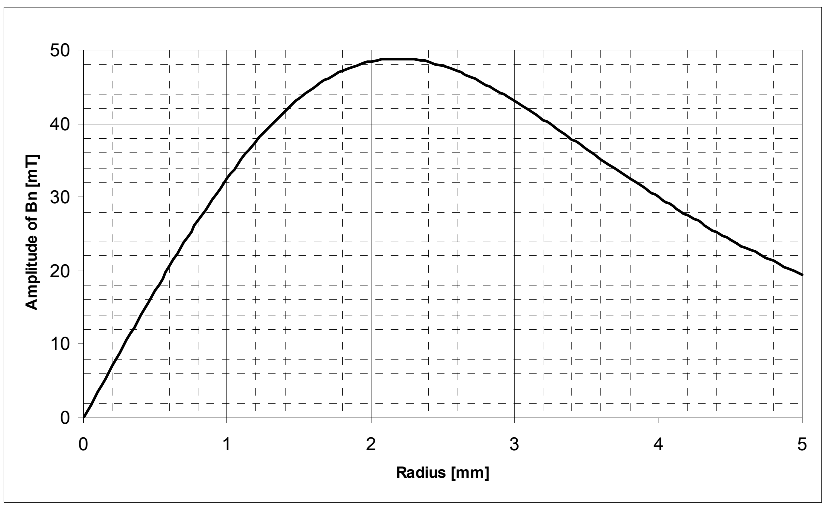

Figure 3: Amplitude of modulation at different radii and fixed distance to the magnet

The amplitude of magnetic modulation B_n changes with the distance between the magnet and the sensors as seen in Figure 4. The sensor radius is fixed at 2 mm. The amplitude of magnetic modulation directly affects the encoder sinusoidal signal level. Therefore the distance control between the sensors and the magnet is important.

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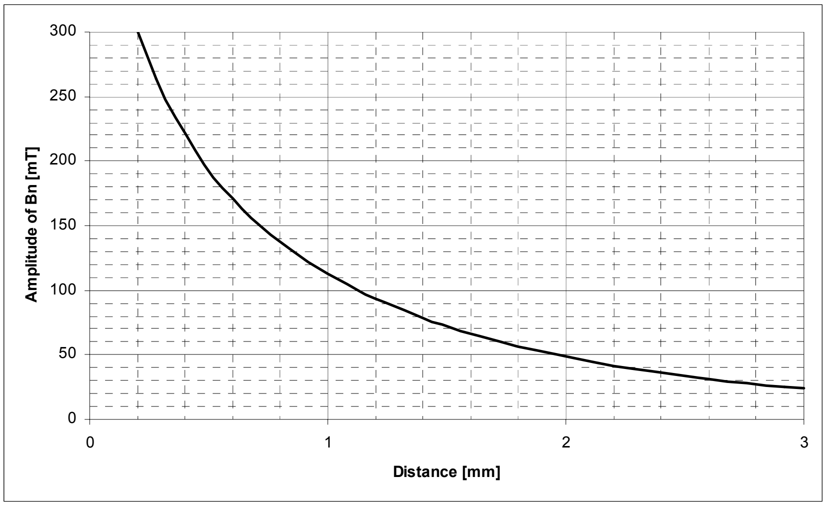

Figure 4: Amplitude of modulation at different heights and fixed radius to the axis of the magnet

The offset of magnetic modulation B_n changes with radius over measurements made with a fixed distance between the magnet and sensors. Figure 5 shows how offset changes with radius. Distance between the sensor and the top of the magnet is fixed at 2 mm.

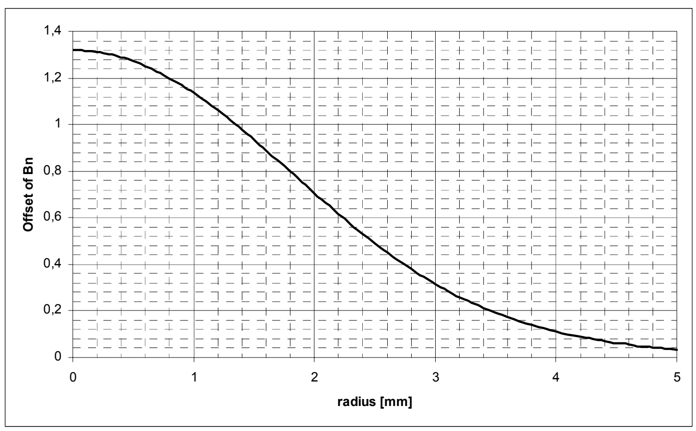

Figure 5: Offset of modulation measured at different radii and fixed distance to the magnet

Positional error

Positional error is the difference in position between the actual position and the given encoder position. It is often called “integral nonlinearity” or “sub divisional error” (SDE).

To minimise interpolation errors the sine and cosine signals must be of good quality. Potential errors on the sinusoidal signals are:

- Harmonic distortions
- Offset of sine and cosine signals
- Phase difference between sine and cosine signals
- Amplitude differences between sine and cosine signals

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Harmonic distortions of the sinusoidal signals can be minimised by using a good shape magnet. With a good shape magnet the SDE caused by harmonic distorted signals is normally in the range of 0.04 °. The remaining errors on the sinusoidal signals are caused by the processing electronics and misalignment of the sensors with respect to the magnet. A typical SDE error plot can is shown in *Figure 6*. With a good choice of components and careful installation the peak values can be reduced to around 0.1 to 0.2 degrees.

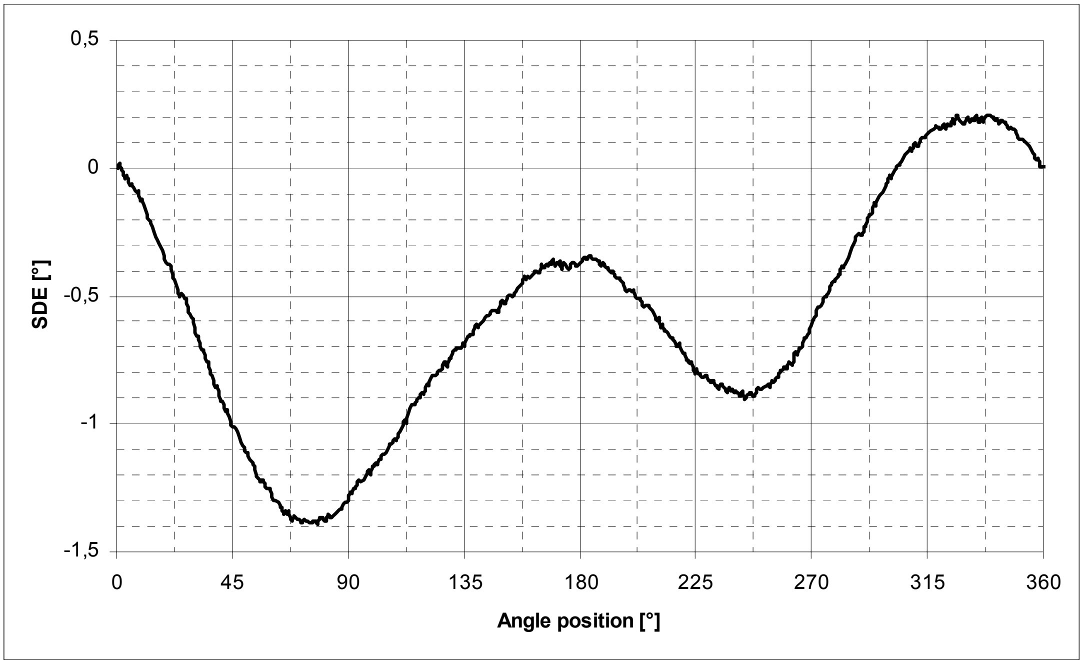

Figure 6: Typical SDE plot

Positional error caused by processing electronics

Compact magnetic encoders have Hall sensors integrated on silicon along with the processing electronics. During silicon production, small errors can occur in the circuit which can result in offset, phase and amplitude difference errors. A good magnetic encoder chip should have built in correction for minimising these imperfections. Each chip must be measured and corrected to ensure optimum performance. However, the corrections are made at room temperature and at nominal power supply voltage. When the chip is operating at high temperature, the electronics can generate additional positional error. A good silicon design should compensate for this temperature effect. A small change of supply voltage can also result in additional positional error. Therefore, it is important that power supply voltage is stabilized to the recommended value.

Positional error caused by axial misalignment

Hall sensors are arranged in a circle with a radius of around 2 mm. SDE can occur when the centre of the sensor circle is not aligned with the magnet rotation axis. With correct alignment each sensor senses the same amplitude and offset of modulation so that differential reading can cancel any offsets. If the centre of the sensors is

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displaced, each sensor senses slightly different magnetic modulation amplitude (see *Figure 3*), slightly different magnetic modulation offset (see *Figure 5*), and the sensors have slightly different angles to the centre of rotation. Each error has different behaviour and they will be described separately. We will mark the SDE caused by bad quality magnet with offset as “SDE type 1” and the rest of the error “SDE type 2”. The SDE type can be recognized by the shape of the SDE.

SDE type 1

This type of SDE is sinusoidal in shape with one period per revolution. The amplitude of SDE is linearly dependent on magnet quality and the amount of displacement. This SDE type can be reduced or removed with good quality magnets. The magnets from suppliers can have offsets in the range of up to 10% of modulation, where as the acceptable value is up to 1%. If the offset is in the range of 1% of modulation amplitude then the SDE is increased by 0.15 ° for each 0.1 mm of displacement. In practice it is often necessary to reject up to 80% of the magnets as the magnetisation is not consistent.

SDE type 2

This type of SDE is sinusoidal in shape with two periods per revolution. The amplitude of SDE is nonlinearly dependent on the amount of displacement. This type of SDE can not be eliminated (with a good quality magnet), however larger diameter magnets can give lower SDE at the same amount of displacement (see *Figure 7*).

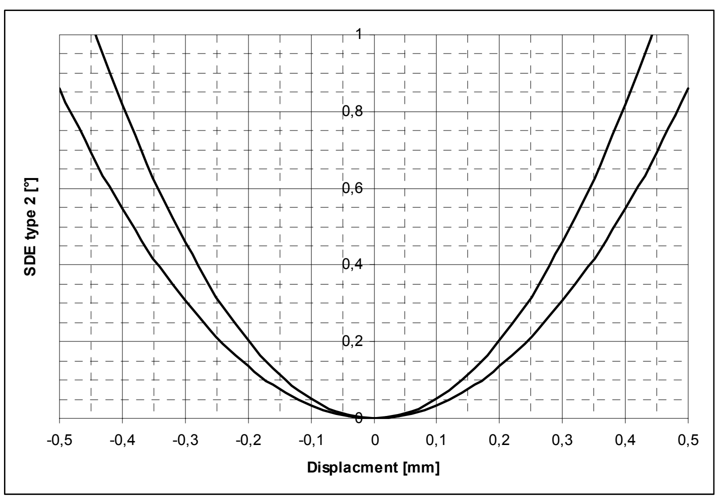

Figure 7: SDE type 2 for 4 mm and 6 mm diameter magnet

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Noise

There are a number of noise sources for such an encoder, the main source though is noise from the hall sensors themselves. The peak noise for a well-optimised system is normally in the range of 0.02 °. This is one of the reasons that resolution for such devices is limited to 13 bits (~8000 counts).

The noise can be reduced by:

- reducing the distance between the sensors and the magnet but this is not always possible.
- biasing the Hall sensors with maximum current to improve signal to noise ratio but this will result in increased power consumption.
- Increasing filtering of sinusoidal signals but this will result in delays in the outputs.

Cost considerations

There are a number of hidden costs to understand when choosing any such onaxis encoder. Depending on the application, a number of factors should be considered.

Installation costs – to achieve best performance you have to carefully position the encoder chip as well as the magnet. Some manufacturers include functionality within the chip for the customer to remove small errors or assist with positioning. Although this sounds like a good solution it is often too time consuming for volume manufacturing. Therefore it can be more economic long term to purchase a modular or packaged solution. The manufacturer of this module or encoder will optimise the performance against the mounting face or holes.

Magnet selection – the magnet should be made of a suitable material to survive the environmental conditions of the application such as temperature. Once the magnet material is chosen the polarization should be sufficiently accurate to achieve the required performance. Some encoder manufactures also offer suitable magnets that have been 100% tested to guarantee performance of the installed system. Using magnets that have not tested can produce inconsistent results.

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