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Surprising Advances in Magnetic Encoder Performance – do not expect only better Accuracy

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Abstract

Magnetic encoders have been viewed as low end solutions for many years. German BOGEN Electronic GmbH, reknown for highly accuracte magnetic scales, and the Portuguese INESC institute have teamed up in the European innovation project tuMaPos to improve magnetic encoder accuracy. The first products from the tuMaPos project have now achieved accuracy levels which surpass low end optical encoder performance, while retaining the cost and technical advantages of magnetic measurement. In parallel other new advantages have been achieved, that provide engineers and designers with more possibilities for integrating position measurement in their products.

After a short history of magnetic encoders the presentation focuses on market requirements, new approaches and recent implemented improvements. The different magnetic reading technologies, such as using Hall effects and different magnetoresistive principles, plus their impact on accuracy will be discussed. At the same time, different approaches for improving scale accuracy are presented. A comparison between optical encoders and magnetic encoder performance underlines, that magnetic encoders have made a giant progress and bring some surprising new capabilities to the market.

The presentation provides users with guidelines how to take advantage of the performance leaps of magnetic encoders and how to achive best accuracy and resolution using magnetic encoders. A short outlook on the future research roadmap highlights areas, where further advances can be expected in the near future.

Key words

magnetic encoders, magnetic scales, magnetic measuring systems, measuring technology, measuring accuracy

History of magnetic encoders, magnetic reading technology and their use

The first magnetic readers in wide use were inductive read heads for audio recording. They were also used for position measuring experiments for numerical controlled machine tools. With the continuous advances in information technology came the need for a higher density of information on magnet memory (hard disk drives). Hall effect sensors were used for reading data, stored as magnetic information, and later led to the implementation of anistotrop (AMR), giant (GMR) and tunnel (TMR) magneto resistive reading heads.

Meanwhile, the first magnetic encoders were based on Hall effect sensors. The Hall sensors were used for on-axis measurment of rotation using dipole magnets and in switching applications for discrete position measurement. Later, Hall arrays were used for multipole position measurement. As Hall sensors are cheap, they are used extensively for high volume applications, such as automotive. Typical Hall sensor applications in a car are the wheel rotation determination for the ABS or cam shaft applications driving the fuel injection timing.

Then AMR sensing technology was used to read positions, typically for reading multipole magnets for linear and off-axis rotary applications. Many magnetic measurement solutions today are based on AMR technology. AMR provides better spatial resolution than Hall *technology, but tend to be more expensive than Hall sensors.*

The GMR technology was used next and has been widely used for gear tooth reading for rotary applications, switching applications and on-axis measurement. Many new application developments are based on GMR technology, as it provides more sensitivity than existing Hall effect and AMR sensors.

In the last few years, TMR sensors have been widely implemented for on axis sensors and the application moves slowly into innovative uses. It is expected, that the TMR technology will replace other technologies.

Based on the application case, Hall effect is used for many applications with low accuracy requirements. Many automotive applications today are using Hall effect sensors, as the accuracy is sufficient. Electrical engines for cars are requiring higher accuracy and will require a shift away from Hall effect sensors.

Accuracy in magnetic measurement *systems and the effect of scale accuracy*

A design engineer needs to know, what the worst case scenario of his systems position is. For any measurement or positioning system, the complete system accuracy is the combination effect of all component accuracies and the impact of the different components interacting with one another.

The accuracy of a positioning system is defined by the scale accuracy, the sensor accuracy, the performance of the data processing, the quality of the positioning system and mechanical disturbances plus variations.

The accuracy of a sensor is based on the linearity of the measurement. Typically, the measurement of the sensor can only be based on an ideal scale. The better the scale the better the linearity of the measurement can be achieved. The effect of scale inaccuracy will effect the accuracy of the sensors.

The mathematical models of the required sine/cosine interpolation will impact the accuracy. The better the interpolation system, the better the accuracy. As some magnetic sensors work with a 16 Bit interpolation, the impact of lower quality interpolation errors is becoming obvious.

The sensors will have different reading results based on the variations in the production process. High accuracy sensors require calibration for perfect results.

The mounting of the sensors and the movement variation in different directions and angles will impact the measurement result as well.

The scale accuracy can be measured based on the pole length or the pole position. Typical measurements are

- *Single pole deviation*
  For a scale with a certain scale increment size, the scale accuracy based on pole position describes, what the deviation of the actual position of the scale increment to the ideal position is. A magnetic scale with a pole pitch of 2 mm is supposed to have the pole borders exactly every 2 mm. If a pole border is not at the ideal position, the difference between the actual measured position and the ideal position is measured. This difference is called single pole border deviation. On a scale, each pole border is measured and the maximum single pole border deviation per meter describes for many suppliers of magnetic scales the accuracy class of the scale.
- *Total pole deviation*
  Total pole border deviation is viewed as the maximum minus the minimum pole border deviation. So if the scale has a maximum of +17 µm and a minimum of -14 µm, the scale has a total pole border deviation of 31 µm. This measurement describes the total range of errors in a scale.
- *Pole length deviation*
  The pole length deviation is calculated for each pole as the difference between the pole borders, typically minus the nominal pole length. The maximum and minimum pole length deviation is again the total pole length deviation.
- *Cumulative pole length deviation*
  Cumulative pole length deviation is summing up the pole length deviations from the beginning of the scale to each pole. This number is documented for each pole. Then the minimum and the maximum value from the sums of deviations are determined. The difference between the maximum and the minimum is the cumulative pole length deviation.

Magnetic scales have a major impact on the accuracy of the measurement system. Typically, for shaft end applications, the quality of dipoles are the driver of overall system accuracy. Since the magnetization process leads to a low quality, many approaches have been tried to select the best dipoles for high accuracy operations.

Magnetic multipole scales have been successfully used and many different approaches have been implemented to achieve high accuracy. While some applications are only requiring low accuracy, the highest accuracy that can be reached with magnetic scales is 3 µm per meter single pole deviations.

The tuMaPos approach to improve accuracy

The EU-funded (SME instrument) innovation project tuMaPos has been targeted to improve magnetic encoder accuracy. Through several different approaches, the project has combined new MR technologies with higher accuracy scales and achieved a performance leap in accuracy.

There are two keys to improve accuracy: Decreasing the scale increment size to reduce the errors in interpolation and improving the scale accuracy. A highly accurate magnetic measurement system is consisting of two equally important parts: The magnetic scale and the magnet sensor. Without an accurate written scale, the best sensor cannot compensate the missing accuracy the scale provides. Lacking a good sensor, the most accurate scale is worthless.

The tuMaPos project is working on both fields using the advantages of XMR technology. With smaller increments, that can be written more accurately, the sensor can use less interpolation to achieve a high accuracy.

Writing smaller scale increments propels scale accuracy in the foreground. If a 1 mm pole pitch scale can be written with an error of 1%, the scale will have a single pole deviation error of 10 µm per meter. For a scale with a pole pitch of 100 microns, the same error will represent 10% of the increment. For achieving the same performance as a 1 mm scale with 1% the scale requires an accuracy of +/- 1 µm.

So the target of the tuMaPos project is to achieve a higher accuracy in the scale while reducing pole pitch. If the pole pitch can be shortened and the error can be reduced, together with a sensor that reads smaller pole pitches, a higher accuracy can be achieved.

Achieving smaller pole pitches requires a new mechanical design of the production process as the existing systems are not designed to support the required accuracy levels. New systems need to be implemented and designed to achieve the production quality required. The implementation will lead to scales that will be better than +/- 3 µm.

With a very highly accurate scale, the requirement is to read smaller pole pitches. Existing pole length dependent sensors are available for a small subset of possible values. Many typical AMR sensors are optimized for 5 mm, 2.5 mm, 2 mm, 1 mm or 0.5 mm pole length. These sensors cannot be used with a much smaller pole length.

The key task was to develop a sensor, that can read smaller pole pitches. Comparing the performance of Hall and the existing AMR sensors, the magneto resistive sensors provide a better performance. Even better performance is offered by GMR or TMR sensors. For a better performance, the most crucial factor for this task is the signal-to-noise ratio (SNR) which describes how well the signal can be separated from the noise.

The higher the SNR, the better the reading of the magnetic pole information. If the magnetic remanence of the scale is stronger, than the sensor can work easier. Unfortunately, the remanence from smaller scale increments will get smaller rather than stronger. Comparing the different results, the team decided to use the more advanced technologies to develop sensors to read smaller pole pitches. The main advantage of the TMR and GMR technology over AMR and Hall effect sensor is the better signal strength coming from a much bigger effect of the magnetic field on the magnetoresistance. The TMR reaches up to 600% magnetoresistance effect, compared to around 100% for GMR and much less for AMR. The signal is stronger and needs therefore less or even no amplification - which is introducing another source of noise - for further processing.

This advantage is used in the tuMaPos approach to pursue the goal of allowing the measurement of smaller pole pitches. There is another - surprising - effect of this performance improvement: With the better signal to noise ratio, it is possible to increase the reading distance of magnetic encoders. Compared to existing AMR sensors, the new sensor technology can more than double the reading distance between scales and sensors using the same pole pitch.

Guidelines how to take advantage of magnetic encoder improvements

The enhanced performance of the X-class encoders provides the user with more design flexibility than typical magnetic encoders.

Already today, magnetic encoders surpass optical encoders in flexibility. Magnetic scales can be easily produced for different length, different patterns and different number of tracks. Instead of fixed scale designs, magnetic scales can be adapted easily to many different geometrical shapes. Due to the dirt resistance, magnetic scales do not need to be encapsulated. Other than optical encoders, which are typicallly added as a separated block at the end of motors, magnetic encoders can measure where it matters. Magnetic measurement solutions excel, when a linear movement needs to be measured in a dirty environment or where a shaft movement needs to measured. As magnetic scales can be produced to a diameter of upto two meters, they can provide a very high accuracy where needed.

As s key design benefit, magnetic measurement can be placed, where it matters. Since rotary magnetic scales can be created not only axial but also radial, they can open new product architectures. Since the rotary scales are not created by wrapping a linear scale around a rotor and thus avoiding a mating point, but are created with true angular division, they provide 360° degrees of equal performance.

But now there is much more design flexibility available. The key enabler for new design rules is the high reading distance. The distance improvement of the X-class encoders allows much more design freedom and completely new design features:

- *High reading distance allows new designs for critical environments. The sensing head can now be placed far away from the scale. Scale and sensing head can be separated by non magnetic material. So a liquid in a tank can be measured through the walls, the sensor can be mounted on the outside, where it does not require as much protection as if it were used inside.*
- *High reading distance allows higher speeds in rotary applications. Higher reading distance allows added protection on the scale~~.~~ The scale can be placed inside a metal part, that is optimized for high speed. The scale will allow much higher turning speed, since it is contained in a high speed housing.*
- *High reading distance allows for new designs. If there are obstructions, where a regular sensor usually would be mounted, the regular sensor cannot be built arround the obstruction.*
- *High reading distance allows for bigger rings, as a radial measurement solution can now deal with more eccentricity than existing solutions. The bigger distance range allows to read the rings in the full turn, and the magnetic encoding process can adapt the eccentricity of the ring during production, if the magnetization process is adapted to this.*
- *The high reading distance range allows linear movement measurement with a non perfect alignment. The results of this can be read in many different environments.*

The effects of the higher reading distance cannot be described easily, but time will tell how much the new performance will lead to new product designs.

Roadmap for further advances in magnetic encoder performance

Since user requirements for higher accuracy will continue to increase according to a recent study by BOGEN, there are many more approaches to increase the accuracy of magnetic encoders. The market pull will lead to many implementations by different companies.The research team expects many companies to continue to push the development. New reading technologies, such as TMR or even the colossal magnetoresistance effect, will lead to better accuracy in the long run.

Scale accuracy will also continue to be increased. The hard disks of today provide an interesting example of smaller magnetic writing and reading. Todays hard disks write bits in 4 nanometer length and modern data tapes in 60 nanometers. Therefore, smaller pole pitches can be easily achieved and the focus will be, how the mechanical challenges for writing smalle pole pitches with increased accuracy will be overcome.

New magnetic materials such as neodym and new ferrite composites will offer higher remanence and will allow better performing materials.

With the first implementation of 3D printed scales, even more design flexibility can be achieved. Due to existing limitation inherent in the 3D process, scales cannot be produced with higher accuracy. If 3D printers improve their accuracy significantly, this technology may lead to a better scale. Since this means smaller particle sizes, this means also longer processing times, which will reduce the attractiveness for high volume applications.

Engineering ingenuity, material advances and new sensor technologies will pave the path to higher accuracy for a long time. Magnetic measurement solutions will be used more often in future than they are today.