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Practical limitations of accurate magnetic measurements in industrial applications

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Abstract – **The fundamental factors that limit the accuracy of magnetic measurements for field strengths typically encountered in industrial measurements of permanent magnets are discussed. In regions where magnetic fields can be considered homogenous, the accuracy of the measurement is limited by the stability of the magnetometer, the accuracy of its calibration, and the orthogonality of the sensor. However, the field-sensitive volume's size and the measurement axis's orthogonality determine the total accuracy in the near-field region of small magnetic structures. Using measured magnetic images from encoder structures, it is shown that accurate measurements are achieved only by measuring all 3 magnetic field components in a tiny volume.**

I. INTRODUCTION

Magnets are vital in numerous industries, including automotive, electronics, aerospace, and medical [1]. To ensure optimal performance and quality in production, it is crucial to have precise knowledge of the magnetic field distributions of magnetic devices. As the need for magnetic systems that are stronger, smaller, and more intricate grows, measuring magnetic fields with precision has become more exacting. As a result, magnetic measurement systems must become more accurate and faster to keep up with these demands.

This paper discusses the fundamental factors that limit the accuracy of magnetic measurements for field strengths typically encountered when measuring permanent magnets in industrial applications, ranging from a few milliteslas (mT) to several teslas (T). Understanding these limitations and adequately accounting for them makes it possible to obtain highly accurate and repeatable measurements of such magnets, even in challenging industrial environments.

Magnetic fields are inherently three-dimensional, with a specific strength and direction at every point in space. Unlike electrical fields, the distribution of magnetic fields cannot be characterized by a simple scalar function such as voltage. Measuring all three magnetic field components accurately and locally is therefore unavoidable to correctly describe real magnetic systems and draw valid conclusions. This, however, presents a significant challenge for magnetic measurement systems known as magnetometers.

II. MECHANICAL AND ELECTRONIC LIMITATIONS

A magnetometer must be stable, with low drift, and not affected by the external temperature to ensure accurate measurement. The instrument's mechanics should be simple and solid, providing a well-defined point in space for measurements to be taken. NMR-based magnetometers are precise and stable because they rely on the fundamental principle of nuclear magnetic resonance. However, NMR measurements do not provide information about the direction of the magnetic field and are not local. On the other hand, Hall-based magnetometers provide accurate local information about the field’s strength and direction, and they can measure both DC and AC magnetic fields in real-time. Well-designed Hall-based magnetometers compensate for temperature effects and stabilize the drift of the electronics to the extent that their measurements remain accurate within a few 100ppm or less over at least one year. This makes Hall-based magnetometers the instruments of choice for advanced research, development, and industrial applications [2].

III. HOW CALIBRATION AFFECTS MEASUREMENT ACCURACY

Most magnetometers require calibration against a known reference in a homogeneous field at DC. In this situation, the size of the instrument's field-sensitive volume (FSV) does not affect its calibration. However, in real-world scenarios where magnetic fields have strong gradients, the size of the FSV can significantly impact the accuracy of the measurements. For example, suppose a magnetic field has a periodic variation along a straight line with a period of Λ. In that case, the measurement error ε due to the size of the FSV is given by equation 1:

$$\varepsilon = 1 - \cos\left(\frac{\pi W}{\Lambda}\right) \qquad (1)$$

Where W is the width of the FSV along the line. Specifically, a 150µm long sensor will inaccurately measure a periodic magnetic structure with a 10mm period by approximately 0.1%. Although seemingly minor, high-precision magnetometers are accurate to 0.1% or better in homogenous magnetic fields. In our example, the size of the FSV doubles the total error of the measurement, as the FSV error is systematic rather than statistical.

IV. THE IMPORTANCE OF THE FIELD-SENSITIVE VOLUME

To quantify measurement errors caused by the FSV in actual magnetic structures of small size, we used a high-precision mapper from SENIS AG, Switzerland [3], to scan a magnetic encoder tape. This mapper can measure the entire magnetic field of a sample over large volumes with positional repeatability better than 10µm. The SENIS Hall Sensor has an FSV of 100µm x 100µm x 10µm and can measure all three components of the magnetic field simultaneously within this volume, with an absolute accuracy of better than 100µT. To achieve unprecedented resolution in one direction, the sample was scanned so that the smallest dimension of the FSV, i.e., 10µm, was moved along the long side of the sample. Fig. 1 illustrates the measured magnetic distribution over an area of about 5.5cm x 1.5cm, with the three components of the field presented in separate images of red, green, and blue. The combined full-color image depicts the entire magnetic field vector. The fourth image (purple) shows B_{tot}, the field's strength.

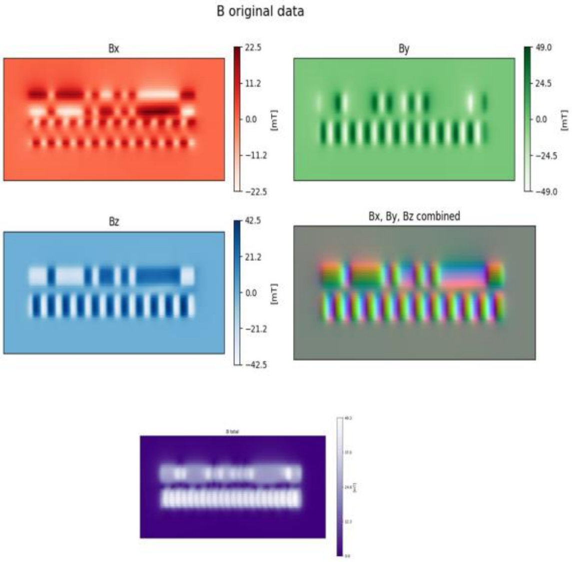

Fig1. Measured magnetic field of an encoder. Red/green/blue are the images of B_x,B_y and B_z. The full color image is the B-vector, the strength of the field B_{tot} is shown in purple.

This measurement reveals two distinct structures: a regularly modulated stripe with a periodicity of 4mm located beneath an irregularly coded strip. The primary directional components are B_y and B_z, with a weaker B_x component. In the full-color image, it is evident that the direction of the magnetic field rotates continuously along the periodic structures, primarily in the B_y and B_z plane. However, the Bx component dominates along the upper and lower edges of the stripes. Although this magnetic encoder may appear simple, its three-dimensional magnetic pattern is intricate. The strength of the magnetic field varies significantly in a localized manner, and the direction of the magnetic field continuously changes from one point to another within a small volume.

Fig. 2 displays the field strength along the center of the lower regular stripe, with the sensing width in the scanning direction measuring only 10µm. By averaging the original data over a given distance D along the center line, we can compare the averaged data with the measured signal strength at the central point to obtain the actual relative error for a sensor with width D. Fig. 3 shows the results.

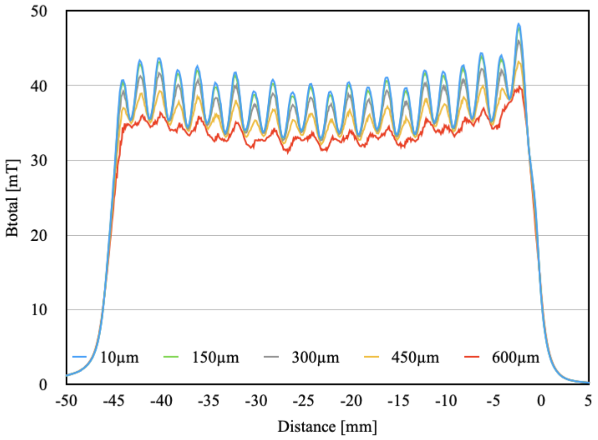

Fig2. Amplitude of the magnetic field for different widths (10µm, 150µm, 300µm, 400µm, and 600µm) of the FSV along the center line of the lower strip.

Even for a tiny sensor of 150µm width, the error associated with the size of the magnetic sensor is greater than 1%. It increases significantly with the width of the FSV. For a 600µm wide FSV, the error related to size is nearly 20%, without considering the inaccuracies of the sensor itself. In fig. 3, these measured errors are compared to the errors that would be expected based on the simple theory presented in equation 1.

The measured errors are nearly twice as large as what simple theory predicts. This discrepancy is due to the complexity of the magnetic structure and depends on the particular case. Theoretical models tend to underestimate the actual errors and should therefore be understood to provide conservative estimates only. This is especially true for small and/or complex magnetic systems. To accurately characterize such systems, measuring all three magnetic field components as precisely and locally as possible is therefore mandatory.

As this simple example shows, it is essential to consider the FSV size carefully when using magnetometers for specific applications. Unfortunately, it is not possible to provide a universal estimation of the total measurement errors for a given measurement system because they depend on various factors, such as the size and orientation of magnetic structures in relation to the sensor itself (distance to the sample, size, and orientation of the FSV for example). Therefore, estimating these errors on a case-by-case basis is necessary. Especially in small, complex magnetic systems or if strong field gradients are present, i.e. in the near-field region of a magnet, the FSV size can be the dominant factor strongly limiting the measurements' total accuracy. In the far-field region, gradients are typically too small for the FSV size to affect the measurement.

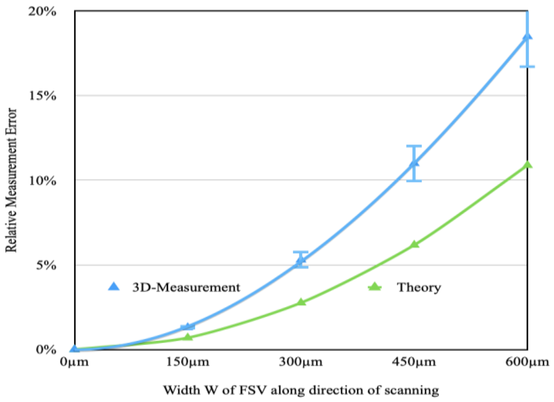

Fig3. Impact of sensor size on measurement error of small magnetic structures

V. ANGLES AND ACCURACY

Magnetic fields are directional, so sensors must be correctly oriented or measure all field components in a small volume to ensure accuracy. Most magnetic field detection technologies, except for NMR, which measures field strength, are only sensitive to one or two field components. As a result, they need to be integrated into sensor systems to obtain the complete 3D information necessary for precise field distribution measurements. When measuring only one or two field components, the manufacturer and the user must ensure the sensor is aligned with the magnetic field vector. Even a slight misalignment of 5° between the field and the sensor will result in a relative measurement error of 0.4%. This effect is also present in homogenous fields. It, therefore, similarly affects near-field and far-field measurements.

The cost and technology limitations for arranging multiple sensors in the same package restrict the FSVs to approximately 1x1x1mm today. This limits the application of such systems to measuring larger fields with small gradients. Semiconductor manufacturing technology is required to build tiny, fully integrated magnetic sensors with smaller FSVs in three dimensions which are capable of measuring intricate high gradient magnetic fields.

Regardless of how multiple sensors are arranged to measure all three directions in space, care must be taken to ensure these sensors point in orthogonal directions. Even minor deviations from orthogonality can significantly impact total field values. Generally, a non-orthogonality of 0.1° between individual sensor axes in an integrated 2D or 3D sensor will lead to an error of at least 0.1% for the total field value somewhere in space. Higher accuracies require measuring along a known given sensor direction or an absolute but not local measurement, such as NMR.

VI. CONCLUSIONS AND OUTLOOK

The accuracy of magnetic field measurements in industrial applications depends on three key factors: First, the magnetometer's mechanics and electronics must be precise and stable; second, the magnetometer must be capable of measuring all three magnetic field components within a small field-sensitive volume, and third, the sensing directions (x,y, and z) must be perpendicular.

Through analysis of magnetic measurements from an encoder, we have shown that for intricate magnetic fields with high gradients, the field-sensitive-volume size can become the dominant factor in measurement accuracy. While magnetometers can have calibrated accuracies of better than 0.1%, non-orthogonality can add several 0.1% to that error. However, careful selection of the measurement instrument and the setup is required to contain the influence of FSV error well within 1%. This is particularly important for near-field measurements of small magnets, where these limitations become significant. But if, for example, one measures the far field or the surface of a large homogeneous magnetic structure, the FSV error can be ignored. In the region far away from the magnet, only the errors caused by non-orthogonality and calibration of the sensor itself remain.

As miniaturization continues to be a prevalent trend across various industries, the need for precise measurement of complex and minute magnetic fields is expected to increase. Manufacturers must, therefore, consider the impact of FSV and non-orthogonality errors in their products to meet this demand. At Senis, we offer the only Hall-based magnetometers and field mappers that can accurately measure all three field directions in a minimal volume. Our latest device, the magnetic camera, boasts 16,000 pixels, each pixel having an FSV of 27 x 9 x 4 micrometers. This small FSV enables accurate measurement of the near field of tiny magnets. This instrument can fully characterize a magnet by concurrently measuring the field distribution at 16,000 points within seconds.

REFERENCES

[1] Magnetic Materials Market - Global Industry Assessment & Forecast, Market Report from Vantage Market Research, 2022

[2] R. S. Popovic, “Hall Effect Devices”, 2nd Edition, ISBN 9780750308557, published December 1, 2003, by CRC Press

[3] For more information about Senis, visit: www.senis.swiss