Testing the Homogeneity of Magnets for Rotary Position Sensors

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Abstract – Inhomogeneity of the magnetic field around the magnet used in magnetic angle sensors affects the accuracy of the rotary position sensor. The set-up for testing the homogeneity of the field of small rotating permanent magnets must meet several conditions, including the following: the two-axis magnetic field probe used for the test must be placed very accurately at the centerline of the rotation axis of the magnet, the offsets of probe measurement channels must be canceled, magnetic sensitivities of the measurement channels must be equal, and sensitivity vectors of the measurement channels should be mutually orthogonal. In this paper we describe a procedure that leads to fulfilment of these conditions. In order to align the probe position with respect to the magnet rotation axis, we roughly scan the magnet, establish a misalignment error function, and then calculate the position of the minimum of this function. The position of the minimum corresponds to the rotation axis. Then the center of the sensitive spot of the probe is precisely aligned with the axis of rotation, and the corrections of the offsets, amplitude mismatch and shift are done. These corrections are performed by using the Fourier analysis of the probe signals. After the probe alignment and the corrections, the homogeneity error is reduced for a factor of 6 to 7, and the residual error is of the order of the noise of the applied Hall probe.

***Index Terms*— Angular error, Hall sensors, Homogeneity of magnetic field, Magnetic angular encoder**

I. Introduction

Modern magnetic rotary position sensors consist of a combination of a rotating permanent magnet and a 2D magnetic field sensor (Fig. 1a). The magnet rotates in the plane parallel with the xOy plane. The magnetic field carried by the permanent magnet should be homogeneous in the area in which the magnetic sensor is placed. Imperfections of the magnet material may cause local field deviation and eventually result in angular errors. For this reasons, the homogeneity of the magnetic field of the magnets to be applied in rotary position sensors has to be measured.

Fig. 1b shows the case with the homogeneous and with the inhomogeneous magnetic field. In the case of the homogeneous field, the magnetic sensor will register a correct rotation angle α_r independently of its position M. In the case of the inhomogeneous magnetic field, which is the case with small magnets, the angle measured by the magnetic sensor α_m is not equal with the rotation angle α_r. The magnetic field homogeneity (H) can be defined as the difference of the measured angle and the real rotation angle:

$$H = \alpha_m - \alpha_r , \quad 0° \le \alpha_m < 360°, \; 0° \le \alpha_r < 360° \qquad (1)$$

Here the angles near 360° are excluded in order to avoid the problem with angular wrap at 360°.

If the magnetic sensor was placed exactly in the magnet rotation axis, the measured angle would not be dependent on the magnetic field homogeneity, i.e. it always corresponds to the real rotation angle. Therefore, the angle measured at the rotation axis is considered to be the reference angle. The rotation angle can be measured with Hall sensors measuring the magnetic field components B_x and B_y. Then the equation (1) could be put in this form [1]:

$$H = arctg\frac{B_y}{B_x} - arctg\frac{B_y}{B_x}\bigg|_{x=0,\,y=0} \qquad (2)$$

According to equation (2), one could measure the homogeneity of a magnet by measuring the two components of a magnetic field at the rotation axis of the magnet and over the area of interest around the axis. But the problem is how to place the Field Sensitive Volume (FSV) of a 2-axis magnetic field probe exactly at the axis of rotation of the magnet. This problem has not been treated in the literature so far. Most magnetic sensors are integrated devices that are assembled in a plastic or ceramic housing. The position and orientation of these packages are subject to mechanical tolerances. The packages do not have the mechanical properties for accurate positioning. In addition, equation (2) is valid only if the applied 2-axis magnetic field probe meets the following requirements: the magnetic sensitivity of X and Y channels of the probe are equal, sensitivity vectors of the measurement channels are mutually perpendicular, and the offsets of these channels are null [2].

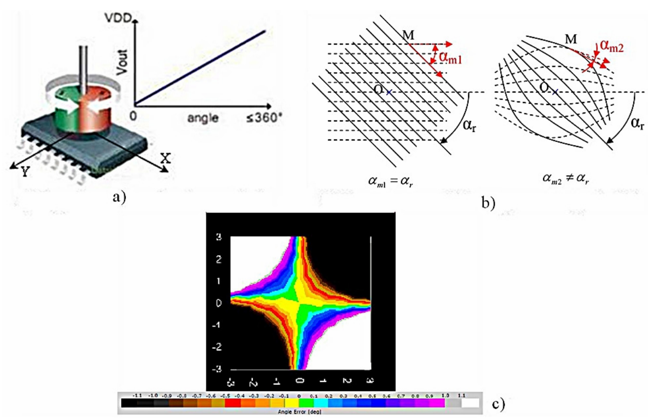


Fig 1. Definition of the problem: a) Rotary position sensor with a linear output; b) Homogeneous and inhomogeneous magnetic filed; c) Measurement of the angle error according to equation (2), i.e. homogeneity for radial magnetization.

In this paper we describe a procedure of aligning the FSV of an integrated 2-axis Hall probe with the rotation axis of the magnet under test and, subsequently, the procedure of in-situ correction of offsets, sensitivity mismatch, and orthogonality error of the used Hall probe.

II. ALIGNING THE SENSITIVE VOLUME OF MAGNETIC SENSOR WITH THE AXIS OF ROTATION OF THE MAGNET

If the Hall probe is in the axis of rotation it always "sees" the same magnetic field vector which rotates together with the magnet. In that case the measured components of the field B_x and B_y will have only the main harmonic. But if the Hall probe is positioned off-axis, then the inhomogeneity of the field (Fig. 1b) will result in the generation of the high order harmonics. This fact is used to find the exact position of the rotation axis.

The present aligning procedure for concurrence of the axis of rotation with the sensitive volume of the sensor does not require any special tools; it uses the magnet under test for this purpose. The sensor should be positioned approximately in the axis of rotation. The magnet under test is rotating, and the output voltages of the channels X and Y of the Hall probe are measured. The following two functions are the result of this measurement:

$$V_x = f_x(\alpha) \tag{3}$$

$$V_y = f_y(\alpha) \tag{4}$$

where α denotes the rotation angle of the magnet, starting from an arbitrary position.

Then the Fourier analysis is applied on signals V_x and V_y. In order to avoid the border effects in the Fourier analysis and increase its accuracy, we chose that the magnet rotates 10 turns. It is enough to keep only the first two harmonics so that (3) and (4) read:

$$V_x(\alpha) \approx \frac{a_{0x}}{2} + a_{1x}\cos\left(\frac{\pi\alpha}{180°}\right) + b_{1x}\sin\left(\frac{\pi\alpha}{180°}\right) + a_{2x}\cos\left(\frac{2\pi\alpha}{180°}\right) + b_{2x}\sin\left(\frac{2\pi\alpha}{180°}\right) \tag{5}$$

$$V_y(\alpha) \approx \frac{a_{0y}}{2} + a_{1y}\cos\left(\frac{\pi\alpha}{180°}\right) + b_{1y}\sin\left(\frac{\pi\alpha}{180°}\right) + a_{2y}\cos\left(\frac{2\pi\alpha}{180°}\right) + b_{2y}\sin\left(\frac{2\pi\alpha}{180°}\right) \tag{6}$$

where α is the rotation angle in degrees and a_k, and b_k (k = 0x, 0y, 1x, 1y, ...) are numerical coefficients. The coefficients a_0 and b_0 are median (offsets) of the periodic function. The coefficients a_k and b_k (k = 1x, 1y, 2x, 2y, ...) are the amplitudes of the harmonics, and, therefore, $a_k \geq 0$, $b_k \geq 0$.

If the sensor is not in the axis of rotation of the magnet, the higher harmonics will be present in the Fourier order (5) and (6). The ratio of the sum of the amplitudes of the second and the first harmonics of equations (5) and (6) can be used as the measure for the error of overlapping of the probe position and the rotation axis of the magnet:

$$Error = \left(a_{2x} + b_{2x} + a_{2y} + b_{2y}\right) / \left(a_{1x} + b_{1x} + a_{1y} + b_{1y}\right) \tag{7}$$

We can exploit the above theoretical insight to align the sensitive volume of the Hall probe and the rotation axis of the magnet. The best alignment will result in the minimum of the error function. We can find the minimum of the error function by applying the Newton's method of optimization in the following way:

We position the Hall probe in turn at 6 points in the XY plane just above the rotating magnet under test - at the expected center of rotation $P_0(x_0, y_0)$ and also at 5 arbitrary chosen points P_1, P_2, ... P_5 around P_0 – see Fig. 2a. The point P_0 can be determined by an algorithm [1] or chosen in accordance with the previous experience with the mapping machine under consideration. Typically, the position error of the first choice of P_0 with respect to the real rotation center is smaller than 1mm. A reasonable distance between the points P_0 and P_i, i = 1, ..., 5, is about 1/3 of the radius of the magnet under test.

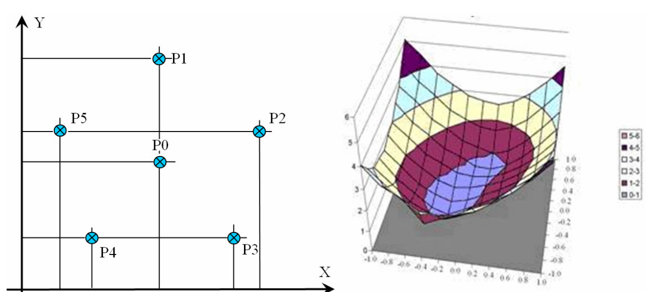
In each of these 6 positions we measure the error function (7). The results of these measurements can be regarded as a function in the table form:

$$Error(i) = f_{er}(x_i, y_i) \qquad i = 1,\ 2,\ ...,\ 6 \tag{8}$$

The function (8) is now presented in the analytical form by using the Tailor approximation [3]:

$$Error_T(x, y) \approx C_0 + C_1(x - x_0) + C_2(y - y_0) + C_3(x - x_0)^2 + C_4(y - y_0)^2 + C_5(x - x_0)(y - y_0) \tag{9}$$

By the substitution of 6 sets of numerical values from the table (8) into the equation (9), the system of 6 linear equations with 6 unknown coefficients C_k, k = 0, 1, .., 5 is generated. By solving this system the numerical values for C_k are obtained.



a) b)

Fig 2. Solution of the problem: a) Example of distribution of calibration points P_i, i = 1, ..., 5, in the surrounding of the nominal calibration point $P_0(x_0, y_0)$, which leads to the 6 "enough"-independent equations for determining the coefficients of the equation (9); b) Concave surface as interpolation of position errors function for a small enough sample region (Δx and Δy).

A. *Calculating the position of the center of rotation*

Partial derivatives of function (9) are calculated, and these equations are equaled to zero:

$$\delta Error(x, y)/\delta x \approx C_1 + C_3(2x - 2x_0) + C_5(y - y_0) \tag{10}$$

$$\delta Error(x, y)/\delta y \approx C_2 + C_4(2y - 2y_0) + C_5(x - x_0) \tag{11}$$

By solving this system for x and y, the coordinates (x_m, y_m) of the minimum of the error function (7) are obtained. The point (x_m, y_m) is the required approximated center of rotation of the magnet.

We can increases the accuracy of finding the center of rotation by an iterative process: we put now P_0 at the previously found approximated center of rotation (x_m, y_m), and then repeat the same procedure as above, but with a reduced distance (for a factor of about 2) between the points P_0 and P_i, i = 1, ..., 5. Typically, after 1 or 2 iterations, the accuracy of finding the center of rotation does not improve any more.

III. QUASI-ERRORS IN HOMOGENEITY DUE TO THE INPERFECTIONS OF THE HALL PROBE

Once the Hall probe of the magnetic field mapping system is aligned with the rotation axis of the magnet under test, the Hall probe “sees” a perfectly homogeneous magnetic field. However, due to various imperfections of the measurement set-up, the actually measured inhomogeneity of the magnetic field may still be present. In this section we shall briefly identify and analyze the main causes of these apparent errors in homogeneity.

A. Errors due to offset and/or external magnetic field

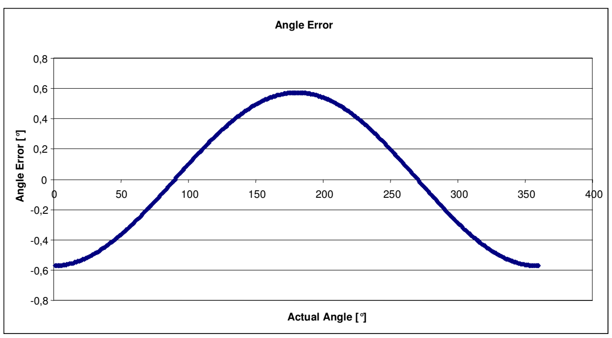


Fig 3. Result of the simulation of apparent homogeneity error of the rotating magnet due to offset and/or external magnetic field along the X axis equal to 1% of the maximal measured magnetic field.

Fig. 3 shows the result of the simulation of the offset and/or external magnetic field influence. Homogeneity error is function of the Sine type, and it has period which equals to the period of the main signal of the rotating magnetic field, and its mean value is equal to zero [4].

B. Error due to sensitivity mismatch

The angle of rotation is typically extracted by using the four quadrant cotangens, which is extracted from the ratio of the X and Y. In the ideal case, the two sensitivities are equal. This is the reason why this measurement principle is not sensitive to the amplitudes of the X and Y signals. But some sensitivity mismatch between the two axes exists even though in our probe the two Hall sensors are on the same chip and the electronic amplification is multiplexed (the same analog chain is used for both axis).

The sensitivity mismatch can be deduced from the ratio of the sensitivity of the channels X and Y, $S_{MIS} = S_X/S_Y$ [4]. In the ideal case is $S_x = S_y$, i.e., $S_{MIS} = 1$.

$$Angle \quad Error = \alpha - arctg\frac{U_x}{U_y} = \alpha - arctg\frac{S_x \cdot B_x}{S_y \cdot B_y} = \alpha - arctg\frac{S_y \cdot S_{MIS} \cdot B_x}{S_y \cdot B_y} = \alpha - arctg\left(S_{MIS} \cdot tg\alpha\right) \qquad (12)$$

Here U_x and U_y denote the analog output voltages of the Hall probe, and B_x and B_y are the measured magnetic field components of the rotation magnet.

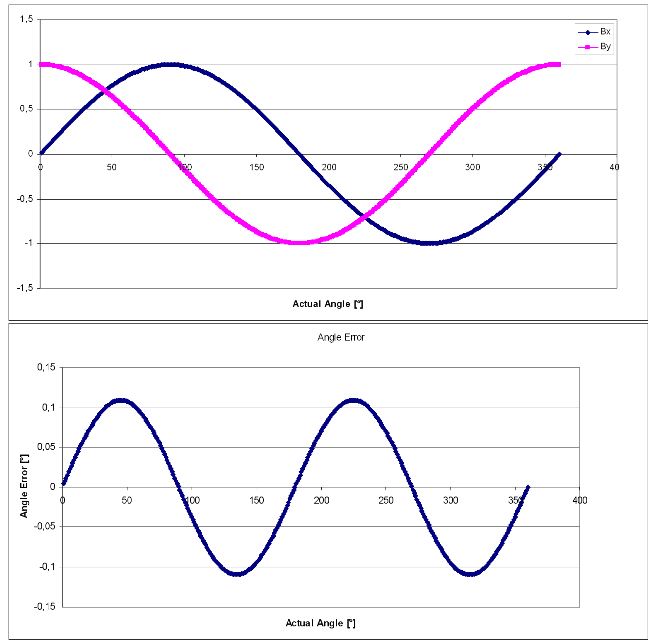


Fig 4. The result of the simulation of the apparent angle error due to unequal sensitivities of the X and Y channels of the probe. The sensitivity of the channel X is 0.4% higher than the sensitivity of the channel Y.

C. Error due to non-orthogonality

In 2-axis Hall sensor based on discrete Hall elements, the angle between X and Y sensors usually deviates by several degrees from the desired 90°. In the case of integrated 2D sensors, where the sensors are parts of the same chip, the orthogonality is guaranteed by the accuracy of the mask and of the integrated circuit (IC) process. Nevertheless, some othogonality error is still present. It is caused by imperfections of the IC process, such as the ion implantation angle, the gradient of the doping level inside the wafer, and mask imperfections.

We can account for the orthogonality error α_0 in this way:

$$U_x = S \cdot B \cdot \sin(\alpha - \alpha_0) \qquad (13)$$

$$U_y = S \cdot B \cdot \cos(\alpha) \qquad (14)$$

Then the apparent angular error is:

$$Angle \quad Error = \alpha - arctg\left(\frac{\sin(\alpha - \alpha_0)}{\cos\alpha}\right) \qquad (15)$$

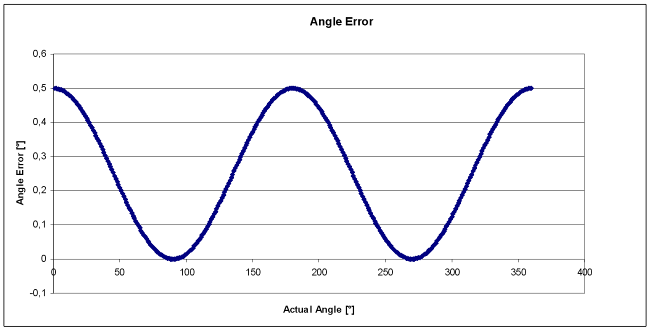


Fig 5. The result of the simulation of the ostensibly error of the homogeneity of the rotating magnetic field due to mutual non-orthogonality of the X and Y channels for 0.5°.

This apparent homogeneity error is a function of Sine type, with period equal to half the period of primary signal of the rotating magnetic field, and its "DC" value, ie. the mean value is:

$$Angle \quad Error_{average} = \alpha_0 / 2 \qquad (16)$$

where α_0 denotes the angular error of mutual orthogonal between channels of the probe [4].

Based on the analysis presented in this section, we can easily calibrate the Hall probe of the magnetic mapping system so that the apparent homogeneity errors of the magnet under test become negligible.

IV. EXPERIMENTAL RESULTS

The experimental verification of the calibration procedure outlined above is done on a commercially available magnetic field mapper shown in Fig. 6 [5]. Magnetic sensor is a 3-axis fully integrated CMOS Hall probe with high spatial resolution (B_y: 0.03 x 0.005 x 0.03mm^3; B_x and B_z: 0.15 x 0.01 x 0.15 mm^3). Spinning current in the Hall devices cancels offset, 1/f noise, and the planar Hall voltage. Magnetic field measurement range is ±200 mT. Magnetic measurement resolution is better than 0.02% and accuracy is better than 0.1% of the measurement range. Scanning spatial resolution is about 5 µm.

For testing purposes a cylindrical samarium-cobalt magnet with diameter of 16.5mm and a height of 2.5mm was used. The maximum field strength in B_{xy} plane is 66mT.

The measured analog signals of the Hall probe are digitized using NI data acquisition card (DAQ). The Fourier analysis of the measured signals is done by means of the LabView function "Extract Multiple Tone Information".

First, the Hall probe was aligned with the rotation axis of the magnet as described in Section II. The alignment accuracy was checked by performing the Fourier analysis of the probe output signals. A typical result of such an analysis is shown in Fig. 7. If the alignment is good, with reference to Fig. 1(b), we expect to see no higher harmonics in the probe signal. This is indeed the case in Fig. 7.

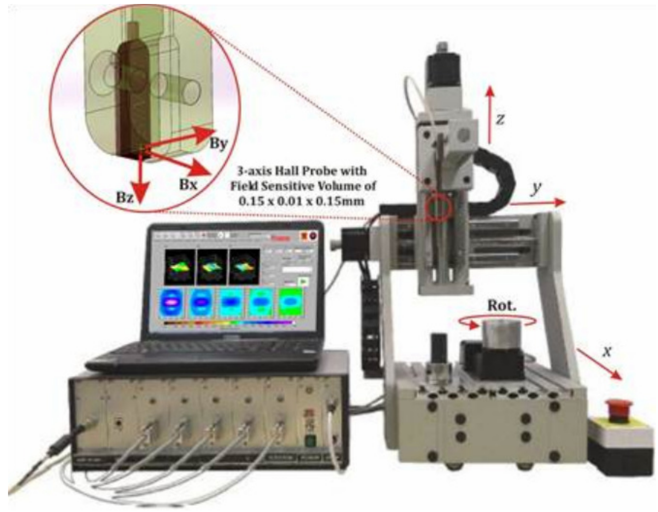


Fig 6. Magnetic field mapper MMS-1-RS

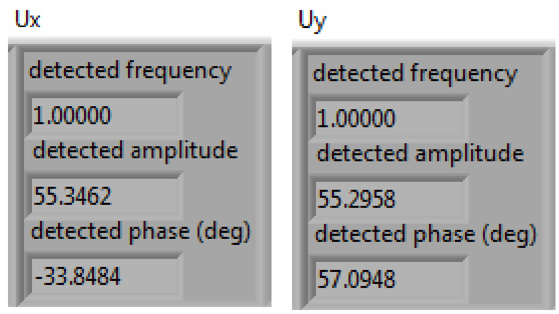


Fig. 7. The results of the LabView Fourier analysis of the Hall probe signals X and Y after aligning the Hall probe with the rotation axis of the magnet. Only the basic harmonic was found. The amplitudes are slightly different (mismatching), and the difference of the phases deviates from 90° (orthogonality error).

Then, with reference to Section III, by using the appropriate software means, we zeroed the offsets, the matching error, and the orthogonality error of the X and Y channels of the Hall probe. The last two errors are visible in Fig. 7.

The result of this procedure is illustrated in Fig.8. The error of measurement system is reduced from 1.1° (before the calibration) down to 0.16° (after calibration) (peak-to-peak value, see Fig. 8). The noise of measurement system corresponds to about 0.04° rms.

The residual harmonic error of the magnetic field homogeneity, which can be guessed from the lower part of Fig. 7, might be due to a slightly non-parallel position of the probe sensitivity vectors X and Y with respect the rotation plane of the magnet. This angular error should produce a magnetic field measurement error proportional to the Cosine of the angle error, and was neglected in the present analysis as a second-order effect.

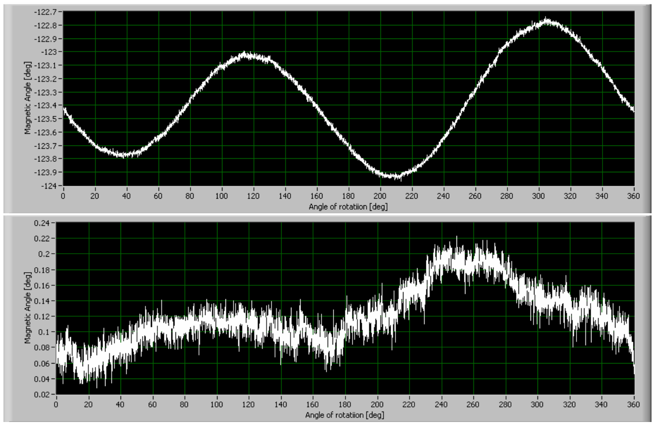


Fig 8. Angle error before and after calibration of the amplitude and phase mismatch in the centre of rotation.

V. CONCLUSION

The described procedure substantially improved the accuracy of the testing of the magnets used in angle sensors. The total accuracy is increased 6 to 7 times.

The advantage of this method is that it does not rely on the accuracy of the used Hall probe: the two measurement channels of the Hall probe do not need to have equal sensitivities. Also, sensitivity vectors of measurement channels may not be strictly perpendicular. And the offsets and the influence of DC external magnetic fields are also cancelled.

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