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ASIC with Internally Generated Dynamic Magnetic Field Imitating External Moving Magnet

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Abstract: A magnetic microelectromechanical system with application specific integrated circuit using array of the Hall elements is presented. It is used for measurement of moving magnetic field, either for its rotary angle or for its linear position measurement. The advantage of the proposed method is to perform an onboard sensitivity testing of the Hall elements without using a complex external magnetic test setup. Evaluation of the integrated circuit is based the internally generated dynamic magnetic field which simulates external dynamic magnetic field. The simulations of the integrated circuit are supported by the measurement results. The verification of the realized system shows very similar behavior compared to the data acquired with the simulated models. Preferably acquired data of spatial distribution of the magnetic field could be used in the process of trimming to evaluate correction factors for offset and sensitivity of the Hall elements or the whole system to yield higher robustness.

Keywords: Magnetic position MEMS, Hall element array, Testing for magnetic position sensor, Rotary measurement, Linear measurement, Harmonic distortions.

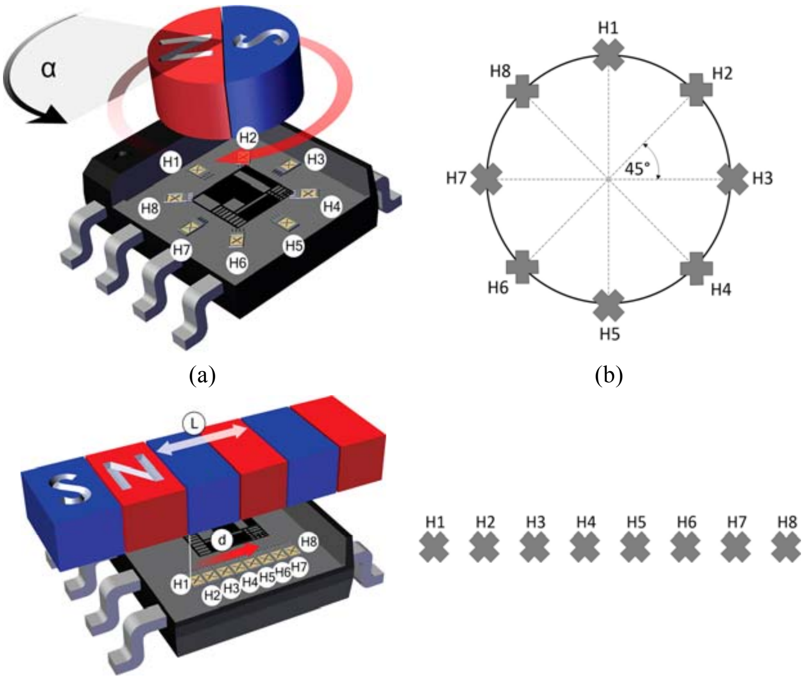
1. Introduction

Hall sensor is a building element of a variety of applications as a basic magnetic field sensing device. Due to its imperfections, a system using it, should introduce techniques to correct sensor errors. To overcome the disadvantage of the offset and asymmetry a well-known method of electrical spinning is used. The sensitivity of the Hall element suffers from temperature, humidity, mechanical stress and packaging. Several solutions coping with it are presented in [1-2]. It is necessary to trim the ASIC (Application-Specific Integrated Circuit) during the production to achieve higher yield. Conventional known test setup approach of trimming with the external magnetic field has the disadvantage of mechanical components placement accuracy. Additionally, this approach is unacceptable for characterization of Hall sensors in mass production as a result of time consuming process and increase of the production cost.

A method for ASIC testing based on an integrated array of micro-coils generating internal dynamic magnetic field which simulates the movement of the external magnetic field during position measurement is proposed [3].

2. Measurement System

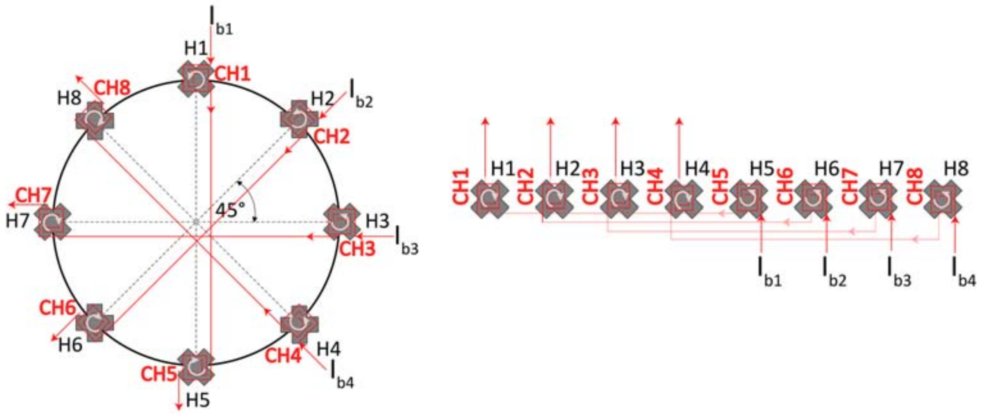
A possible approach for angular position sensing is described in [4-5] but it incorporates complicated interface electronics for a large number of contacts. In contrary the proposed system is capable of measuring linear or rotary external magnet displacement through eight correctly positioned Hall sensors H_i with corresponding micro-coil CH_i as depicted in the Fig. 1 and Fig 2. This approach was proposed in [6] and is known as six terminal Hall element. Placement of integrated micro-coil CH_i above integrated Hall element H_i should not present difficulties in mechanical alignment as both, micro-coil and Hall element have similar dimensions. Detection of external magnet position depends on the system imperfection such as deviation of the sensitivities of the Hall element to each other. Ideally, external magnet location is accurately determined when each sensor element in array together with its corresponding signal processing path exhibits the same susceptibility to the measured magnetic field. Mismatch of each sensor contribution to the measured signal should be evaluated and compensated in the process of trimming. Proposed approach takes the advantage of design geometry (sensors position) to generate almost perfectly symmetrically distributed internal magnetic field and consequently, precisely measures the sensitivity of the system in contrary to the external magnetic field which symmetry is susceptible to the test setup. According to the measurement, the sensitivity of each Hall element could be trimmed either with voltage or current biasing.



(a) (b)

(c) (d)

Fig. 1. On Axis (a, b) and linear (c, d) Hall element placement for rotary and linear measurement respectively.



(a) (b)

Fig. 2. Four testing bias currents I_{bi} of micro-coils for rotary (a) and linear (b) configuration.

3. Procedure of Sensitivity Measurement

Results of sensitivity measurement procedure present a key parameter to successfully trim the system and later precisely measure external magnetic field in the application of interest.

During sensitivity evaluation four micro-coils (CH_1, CH_2, CH_3, CH_4) are tied to externally driven sinusoidal signals I_{bi} phase shifted by 45°. The remaining micro-coils (CH_5, CH_6, CH_7, CH_8) are connected in a way to produce the opposite magnetic field, reducing the number of testing signals by two as shown in the Fig. 2. In case of internal generated testing signals approach with reduced number of signals additionally reduces the power consumption.

Micro-coils testing signals correctly mimic the external rotary magnetic field in case when the phase α_R (equivalent α_L for linear) between signals is the same as the angles between Hall sensors on the circumference for rotary or linear configuration (Eq. (1)). This is true as in both cases, eight Hall elements are distributed under one south and one north pole of the magnet. So the excitation of the micro-coil depends on the real position of the corresponding Hall sensor in the layout. As a result of a Hall element sensitivity mismatch some will produce larger output voltage than others. This can cause nonlinearities in the output signal which is composed of all eight Hall outputs. To evaluate the contribution of pair of Hall sensor only one pair of sensors should be biased.

$$\alpha_L = \alpha_R = \frac{360°}{8} \tag{1}$$

4. Measurement of External Magnetic Field

When the system is exposed to the external field of the diametrically magnetized permanent magnet only Hall elements are biased while micro-coils are not tied to supply node.

Hall output signals are added or subtracted by summation matrix according to the expressions 2 and 3 composed of information out of Hall elements H_i. The resulting signals are $Sin(\alpha)$ and $Cos(\alpha)$ where the α is the rotation angle of the external magnet.

$$Sin(\alpha) = H_1 + H_2 + H_3 + H_4 - H_5 - H_6 - H_7 - H_8 \tag{2}$$

$$Cos(\alpha) = H_3 + H_4 + H_5 + H_6 - H_7 - H_8 - H_1 - H_2 \tag{3}$$

A simple signal processing returns α as tan^{-1} of the ratio of the two signals acquired from Eq. (4).

$$\alpha = \tan^{-1}\frac{\sin\alpha}{\cos\alpha} \tag{4}$$

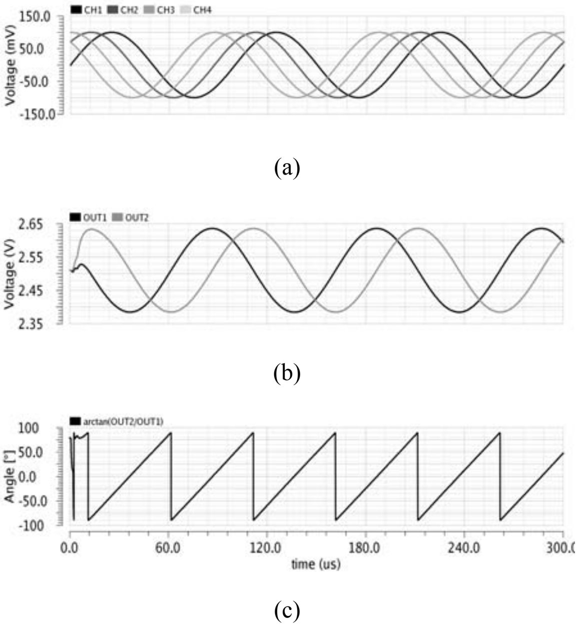
Linear displacement of magnet is estimated according to Eq. (5), where L is the pitch of magnet pole pair north to south, d represents the linear position of the moving magnet and α calculated angle out of Hall elements.

$$d = \frac{\alpha * L}{360°} \tag{5}$$

5. Simulation Results

The integrated circuit is designed in tsmc 180 nm technology and characterized using Cadence Virtuoso environment. The system operates for supply voltage: 3 V-5 V in a temperature range from -40 °C to 125 °C.

Presented simulation results, shown in the Fig. 3, of the system behavior (typical process corner, supply voltage of 5 V at 25 °C) regarding internally generated magnetic field by integrated micro-coils above Hall elements positioned in 45° arrangement. Coils are tied to 10 kHz, 45° phase-shifted sine waves. The response of the system are two output signals representing cosine and sine wave. These two signals have a DC component as the whole system operates around analog ground. The amplitudes of the output signals depend on the sensitivity of the sensors and the gain of the amplification in the signal processing stages.



(a)

(b)

(c)

Fig. 3. Simulation signals: (a) 10 kHz micro-coil testing signals phase shifted for 45°, (b) corresponding output sine and cosine wave and (c) calculated angle.

Simulation of misalignment of the sensors associated with variation of angle in-between them is carried out with a change of phase of a certain micro-coil testing signal. As a result, two output signals have unequal amplitudes. The deviation of the output signal amplitudes is affected by various sensitivity values of each sensor as well. Effect of doubling one Hall element sensitivity in shown in the Fig. 4.

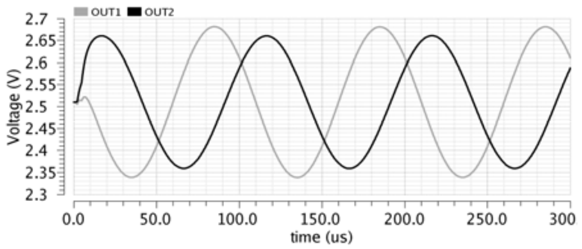


Fig. 4. The deviation of the output signal amplitudes as a result of doubling one Hall sensor sensitivity.

As already mentioned Hall sensors sensitivities mismatch and position misalignment result the error in the output signals. As a result measured angle α is not correct. Deviation from the reference angle, which is acquired in the system with 45° sensor alignment and same sensitivities, is evident in the Fig. 5.

To evaluate harmonic distortions of the mentioned errors, DFT analysis is performed. The spectrum of the output signal *Sin(α)* with a base component at 10 kHz is depicted in the Fig. 6. Upper spectrum (a) shows reference spectrum when sensors are positioned with the equal angle 45° in-between them and the same Hall element sensitivities. Middle spectrum (b) refers to the configuration with one Hall sensor position misalignment of 22.5° and the last one (c) to the configuration with double sensitivity of one sensor. Harmonics are deteriorated with imperfections, so it is essential to properly design layout and introduce trimming procedure with a help of the characterization of a specific sensor through the procedure described in the paper.

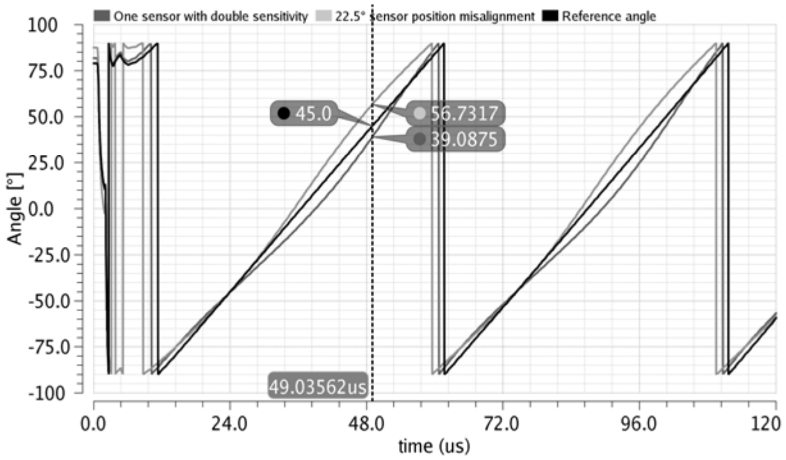


Fig. 5. Deviation of the angles (one sensor misalignment for 22.5° or double sensitivity) from the reference angle (45°, equal sensitivities).

Output signal amplitude is further affected by applying non-uniform frequencies to the micro-coil biasing signals. It calls for testing signals with the same frequencies otherwise higher harmonics distort the spectrum of the output signals.

The specific position of the Hall elements promises reduction of above mentioned disruptive harmonics. The effect of the arrangement of the sensors is more evident when the micro-coil testing signals are distorted. Simulation of the system with 45° arrangement of the sensors shows that the output signal with the base component at 10 kHz has the most critical harmonic at 30 kHz with -54 dBV. This harmonic is considerably reduced down to -92 dBV when the arrangement of the sensors shown in the Fig. 7 is introduced.

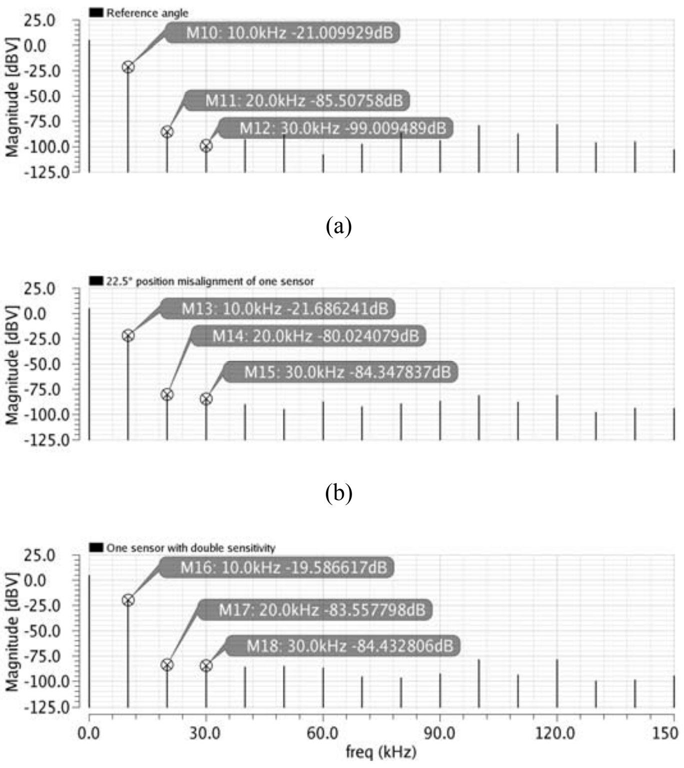
A system incorporating array of Hall sensors has the main drawback - large power consumption as the sensitivity of the sensor is directly proportional to the bias current through the Hall element. Hall sensors consume approximately 21 mA while processing logics and signal processing amplifiers consume 4.3 mA. This calls for power reduction procedure, e.g. adjustment of duty cycle during Hall element operation.

6. Layout

Appropriate alignment of the Hall elements plays a key role to correctly measure magnetic field. Angle in-between Hall elements and symmetry are the most critical parameters otherwise amplitudes and harmonics of the output signals are affected as presented in the previous section. With a specific arrangement of Hall elements distortions as a result of misalignment could be further cancelled out.

Considering SNR (Signal to Noise Ratio), placement of signal amplification circuitry is critical as well. The Hall sensor generates voltages in a range of a few μV consequently it is essential to place the first amplification stage as close to sensors as possible to diminish the influence of voltage drop. Additionally differential signals should be symmetrically driven through the circuitry.

The designed layout of the die with highlighted Hall elements is shown in the Fig. 7.



(a)

(b)

(c)

Fig. 6. *Sin(α)* spectrum of the system with (a) equal sensitivities and equal 45° alignment, (b) position misalignment, and (c) sensitivity mismatch.

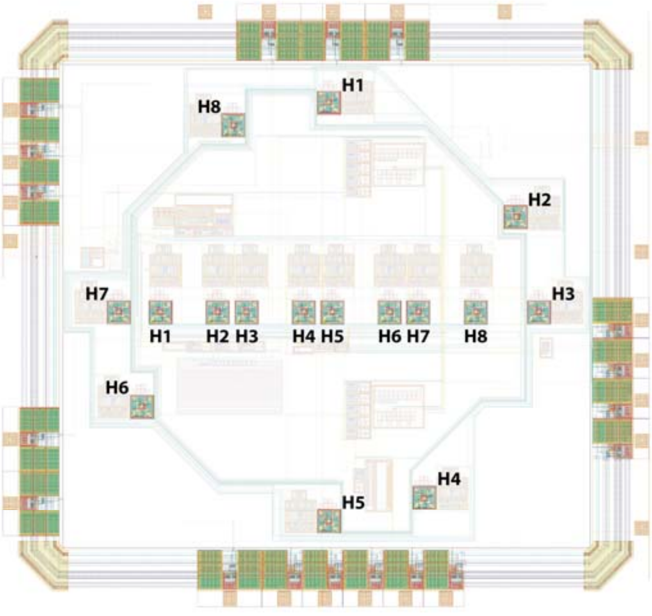


Fig. 7. Layout of the ASIC.

7. Measurement Results

The proof of concept has been demonstrated with a test system using the designed ASIC (Fig. 7). The results cover only rotary approach, while the linear one would need different test setup for external magnetic field excitation. The test has been designed in a way to allow access to the integrated micro-coils of the each Hall element and to monitor the amplified output of each Hall element. It was therefore possible to perform the test according to the proposed method to guarantee internal magnetic field to imitate the spatially moving magnetic field. In the separate experiment an externally generated magnetic field has been applied and the results of both experiments are compared.

The ASIC has been exposed to the external magnetic field generated by a rotating split polarity magnet located in the center of the Hall element array (Fig 2(a)). Each Hall element on the circumference senses sine wave magnetic field of ~500 Hz. In order to clearly present response of the system, Fig. 8 shows only responses of the amplified Hall signals out of the sensors H_1, H_2, H_3 and H_4. Remaining four signals H_5, H_6, H_7 and H_8 are similar but 180° phase shifted.

Sensor signals are processed according to (Eq. 2, 3 and 4) and the overall output signals are sine, cosine and the corresponding angle α of the external magnet. All three signals are shown in the Fig. 9.

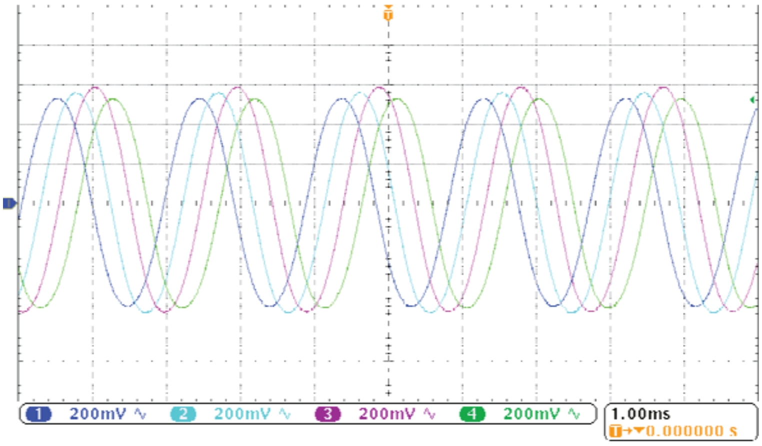


Fig. 8. Responses of the H_1 (dark blue), H_2 (light blue), H_3 (pink) and H_4 (green).

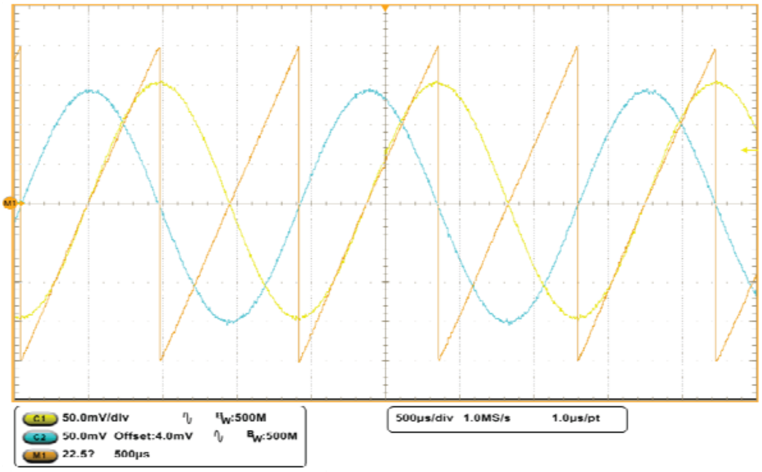


Fig. 9. Output signals: sine (yellow), cosine (blue) and the rotation angle α (orange).

As the simulations indicate that the system is susceptible to the harmonic distortions we performed spectral analysis as well. Fig. 10 shows the base component at ~500 Hz, while the third harmonic is apparent at ~1500 Hz with 48 dB lower amplitude. The accuracy of each harmonic frequency is not only determined by a spectral analyzer resolution bandwidth of 3 Hz, in our case it is mainly limited by a capability of controlling precision of the external magnet rotation speed. Nevertheless deviation of the rotation speed from experiment to experiment is not critical, as higher harmonics of the evaluated signals are enough below the system bandwidth of 50 kHz.

To show the influence of the asymmetrical magnetic field, the center of the magnet was shifted from the center of the sensors circumference. Movement should be large enough to indicate the apparent effect on the transient signal. The center of the magnet was moved in the center in-between the Hall elements array circumference center and H4. The increment of the Hall element response deviations to each other are responsible for unequal sine and cosine amplitudes causing non-linear angle α dependence evident in the Fig. 11.

The misalignment of the external magnet center deteriorates the spectrum as well. Fig. 12 shows that second harmonic is 37dB lower than the base component, while the third harmonic is negligible.

The basic principle of operation regarding the external magnetic field was evaluated, further results cover the response of the ASIC to the internally generated magnetic field.

Generation of the internal magnetic field was carried out with eight micro-coils each consuming peak current of 8 mA. Current of each micro-coil was controlled by the signal generator sources. The internally generated magnetic field was first successfully evaluated up to 10 kHz, but for the comparable results, with maximal achievable external magnetic field, we performed analyses for a frequency of ~500 Hz. The behavior of the angle α processed out of the sine and cosine shown in the Fig. 13 is comparable with the angle acquired in the system which measures the external magnet rotation (Fig. 9). This proves the functionality of the approach for internal generation of the moving magnetic field.

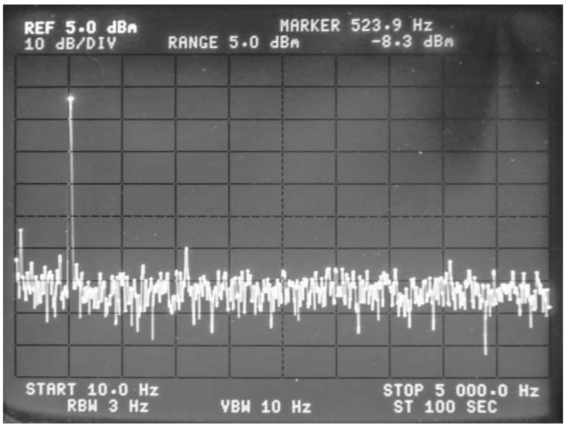


Fig. 10. Sine wave spectrum of the system for the symmetrical external magnetic field distribution.

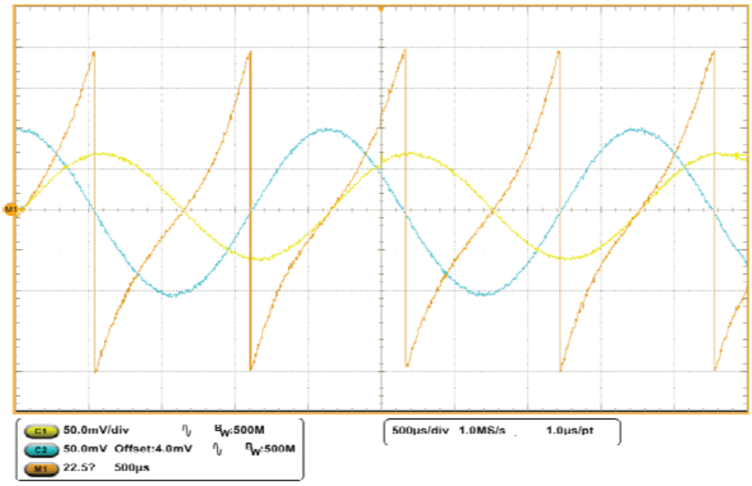


Fig. 11. Unequal sine (yellow) and cosine (blue) amplitudes causes non-linear angle α (orange) calculation.

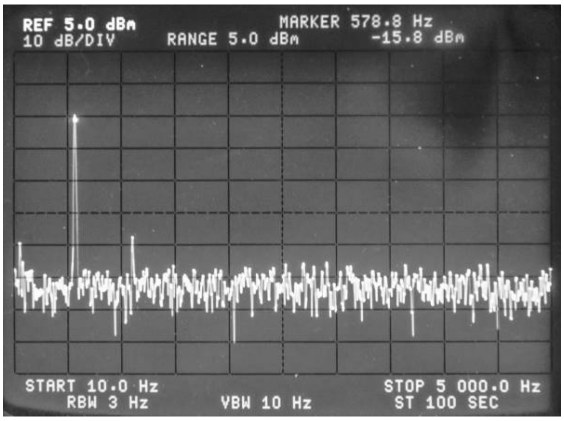


Fig. 12. The spectrum of the sine wave for the setup with misaligned external magnet center.

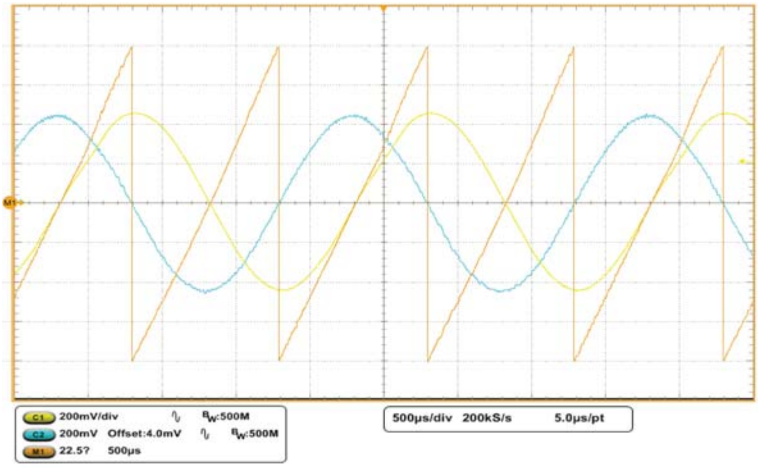


Fig. 13. Sine (yellow), cosine (blue) and the angle α (orange) of the setup with micro-coils generated field.

The second harmonic of the system with internally generated magnetic field is 51 dB lower compared to the base component at ~500 Hz (Fig. 14).

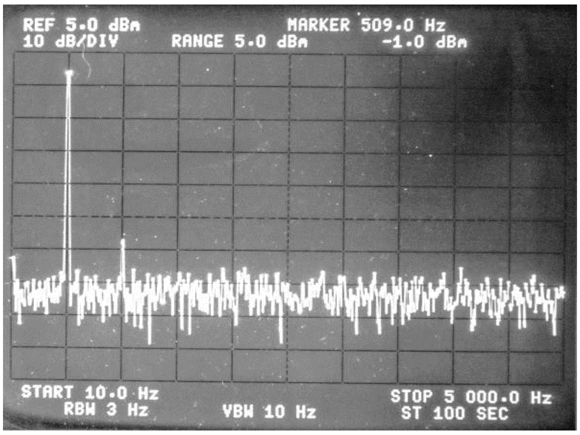


Fig. 14. The spectrum of the sine wave for the internally generated symmetrical magnetic field.

As in the setup with misalignment of the external magnetic field excitation, internally generated field is prone to the non-idealities as well. These originate from unequal micro-coils biasing, misalignment of the micro-coil to corresponding Hall element, disruptive external magnetic field and some others. To demonstrate the effect of the external magnetic field on the internally generated one, static magnet was placed above the ASIC. Amplified responses out of H_1, H_2, H_3 and H_4 are shown in the Fig. 15. The sum of the internal and external magnetic field produces an asymmetrical field that saturates some of the Hall element responses while other Hall elements express lower response amplitudes, causing an angle error.

The angle error is mainly affected by the higher harmonics in the sine wave signal which is evident in the transient signal in the Fig. 16.

The higher harmonics of the asymmetric magnetic field composed of the static external magnetic field and internal dynamic magnetic field are presented with the spectrum in the Fig 17.

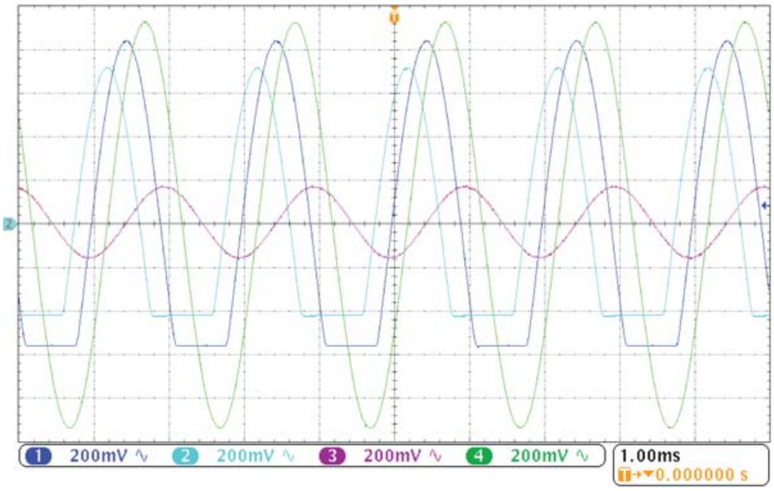


Fig. 15. Response of H_1 (light blue), H_2 (dark blue), H_3 (green) and H_4 (pink) to distorted magnetic field.

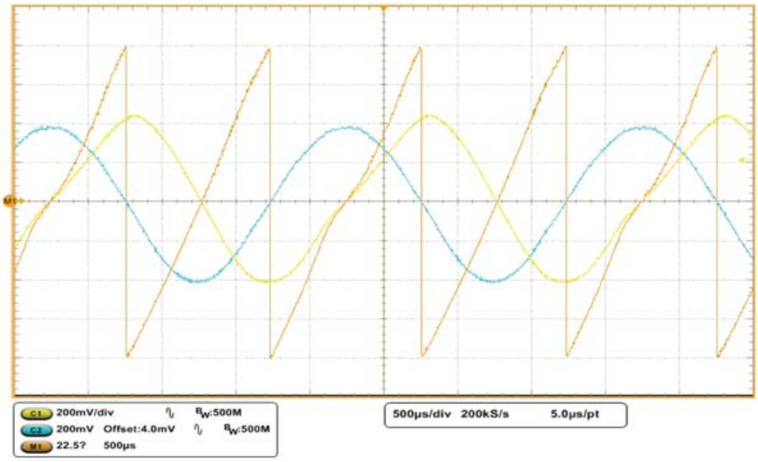


Fig. 16. Sine (yellow), cosine (blue) and the angle α (orange) for the setup with the asymmetrical field.

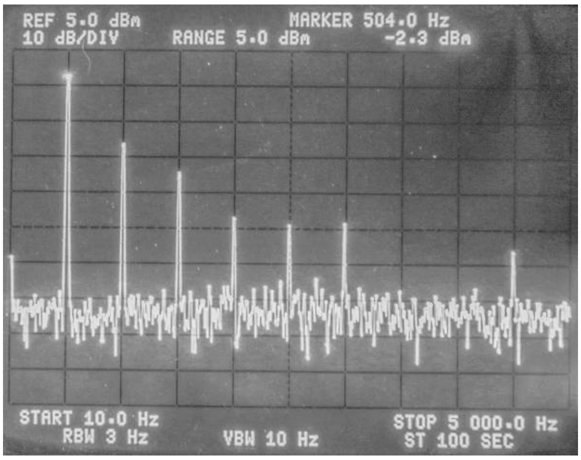


Fig. 17. The spectrum of the sine wave for the asymmetrical magnetic field distribution with base component -2.3dBm and higher harmonics (-21 dBm, -29 dBm, -42 dBm, -44 dBm, -44 dBm and -51 dBm).

8. Conclusions

The paper investigates optimization of the conventional known method of Hall sensors test and characterization method.

The proposed solution is implemented on the system incorporating an array of Hall sensors in order to integrate into applications for rotary and linear measurement of magnetic field. Described approach with an integrated setup can substantially reduce the error of the testing in comparison with the external magnetic field due to poor repeatability and the flaws in the alignment of the external setup. Special care should be taken with the layout as the simulations proved the influence of sensor position misalignment on the output signal, nevertheless specific position of the sensors could diminish harmonic distortions.

Comparison of the ASIC's responses to the externally and internally generated magnetic field proves that the substitution of the external magnetic field with the concept of the internally generated field is functional. The effect of non-idealities shown by simulation results are confirmed with measurement results as well. The proposed concept has a potential to become a valuable tool for a precise characterization and testing of the rotary and linear integrated position sensors. In addition, it provides a possibility to improve the accuracy of the system.

Proposed procedure presents an indispensable approach of acquiring data for the process of self-calibration of the integrated system.

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A. Zhukov, V. Zhukova

Magnetic Sensors and Applications Based on Thin Magnetically Soft Wires with Tunable Magnetic Properties

'Magnetic Sensors and Applications Based on Thin Magnetically Soft Wires with Tunable Magnetic Properties' is inspired by a rapidly growing interest in the development of functional materials with improved magnetic and magneto-transport properties and in sensitive and inexpensive magnetic sensors. The research is demanded by the last advances in technology and engineering. Certain industrial sectors, such as magnetic sensors, microelectronics or security demand cost-effective materials with reduced dimensionality and desirable magnetic properties (i.e., enhanced magnetic softness, giant magnetic field sensitivity, fast magnetization switching etc.). Consequently, the development of soft magnetic materials in different forms of ribbons, wires, microwires, and multilayered thin films continue to attract significant attention from the scientific community, as the discovery of the so-called giant magnetoimpedance effect in these materials makes them very attractive for a wide range of highperformance sensor applications ranging from engineering, industry to biomedicine.

This book aims to provide most up-to-date information about recent developments in magnetic microwires for advanced technologies and present recent results on the remagnetization process, domain walls dynamics, compositional dependence and processing of glass-coated microwires with amorphous and nanocrystalline character suitable for magnetic sensors applications. We hope this book will stimulate further interest in magnetic materials research and that this book can be of interest for PhD students, postdoctoral students and researchers working in the field of soft magnetic materials and applications.

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