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A 3-D Hall Sensor for Precise Angular Position Measurements

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Abstract

A 3-D silicon Hall effect sensor for precise angular-position measurement over 360° rotation is presented. This vector microtransducer functionally integrates into a common sensor region two parallel-field Hall devices for in-plane components of the magnetic field and one orthogonal Hall version for the perpendicular for the chip magnetic field. The advantages of this magnetometer are its low channel cross-sensitivities, remarkable simplified device design and high spatial resolution.

Key Words: Magnetometers, Integrated Hall sensors, Angular position, errors estimation.

1. Introduction

Many different 2-D and 3-D magnetic sensors are proposed in the past for angular position measurements [1–10]. These devices can be fabricated by means of silicon integrated circuit technology, using different phenomena for the detection principle (magneto-resistor, -diode, -transistor, carrier-domain, and Hall element). Despite the higher sensitivity of the separate output channels of the vector transducers using magnetodiodes and magnetotransistors multisensing based on the Hall effect is preferable. The main reason is that this is a well defined and predictable phenomenon with clear galvanomagnetic behavior unlike the bipolar magnetotransducers, which are rather generators of new sensor mechanisms than well elaborated technological solutions [1, 2, 4].

The tested sensor in this paper for angular position measurements is a 3-D silicon vector microsensor, working on the Hall effect principle, using the specific technology of buried Hall devices [2]. These sensors have a very high long-term stability—less than 100 ppm over 20 years. In contrast to other 3-D magnetometers based on the same technology, presented sensor is a compact fully integrated Si device. It measures the direction of the field in the real center of the sensitive area, contrary to bipolar vertical Hall transducers. With such multidimensional sensors, the contactless angular position detection can be performed with high accuracy. Compared with previous works, where only 2-D magnetic sensors were used, we prefer a full integrated vector sensor for this application [1, 2, 10]. The third direction helps with the mechanical positioning of a magnet fixed above the sensor. Measured errors of tilt of the magnet can be used to compensate the distortion of the signal resulting from misalignments.

2. 3-D Hall Effect Sensor for Angular Position Measurements

Figure 1 shows a cross-section of the 3-D silicon vector sensor [2]. The contacts H_1 and H_6, and H_2 and H_5, respectively, are cross-coupled, which increases the signal for the z-component B_z and neutralizes the influence of the other fields B_x and B_y in this output channel. This sensor in essence functionally integrates in one and the same sensor zone two parallel-field Hall sensors for the components B_x and B_y and one orthogonal Hall sensor for the B_z component of the magnetic field. A measuring setup has been chosen to contain operational amplifiers, to regulate equal voltages to the chip, to minimize the lateral parasitic surface currents. These are invoked by the different potential levels of the three Hall voltages generated simultaneously by the B_x, B_y and B_z components. If the supply voltages are not kept equal, false signals may occur.

It has been established experimentally that, despite the simplified device design of the sensor, the cross-sensitivities are about three orders of magnitude lower than the respective channel sensitivities. The output currents $\Delta I_{out}(B_x)$, $\Delta I_{out}(B_y)$and $\Delta I_{out}(B_z)$exhibit a linear and an odd dependence on the magnetic field, their non-linearity factor (NL) in the field range -100 mT $\leq B \leq$ 100 mT being about 0.4%, and in the interval -1 T $\leq B \leq$ 1 T the NL does not exceed 1%.

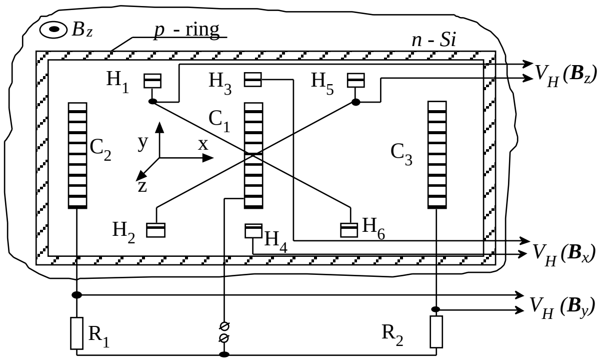

Figure 1. Top view of the 3-D Hall vector sensor.

The magnetosensitivities of the three channels at I_{C1} = 10 mA reach 130 μA/T for B_x, 220 μA/T for B_y and 150 μA/T for B_z, respectively [1–5, 10].

3. Angular Position Measurements

Figure 2 and Figure 3 show the angle dependencies of the Hall currents at rotation of the magnetometer around x- and y-axes, respectively.

As expected the output currents were shifted in phase by 90 degrees. The output signal follows very well the relations $I_{out} \sim |\boldsymbol{B}|\cos\phi$ and $I_{out} \sim |\boldsymbol{B}|\sin\phi$. The temperature coefficient of the magneto-sensitivities for all three channels is 0.1% /°C. The absolute value of the magnetic vector $\boldsymbol{B}$ is given by the well-known operation $|\mathbf{B}| = \sqrt{B_x^2 + B_y^2 + B_z^2}$. The active volume of the 3-D Hall microsensor is about 250 μm × 220 μm × 100 μm. The power consumption at T = 300 K is in the range $W \leq$ 30 mW and does not disturb the accuracy of the device.

There advantages of this sensor are: simplified device, which maximally approaches the original physical cause (this cause is responsible for the measurement of the Hall effect respective vector component); and simultaneous triaxial measurement via separate differential outputs. Thus, the cross-sensitivity of the magnetometer is substantially reduced.

The sensitivities of the 3-D Hall sensor depends on different parameters, the most relevant being the offset, dependence of the temperature and the junction field effect. Methods to compensate these effects are already developed, but in our case they are not used on this sensor in these measurements.

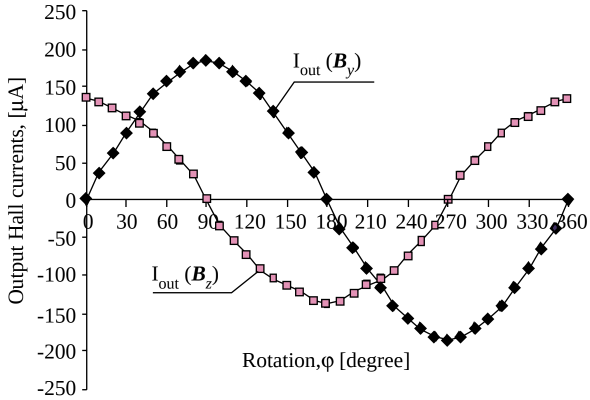

Figure 2. Angle dependencies of the output Hall currents at rotation of the sensor about the x-axis. The homogenous magnetic field B_z is fixed along the z-axis with a value of $B_z = 1$ T; supply current is $I_{C1} = 10$ mA.

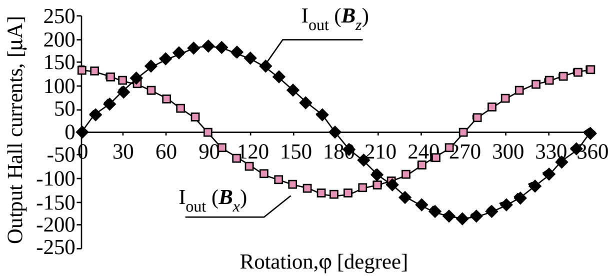

Figure 3. Angle dependencies of the output Hall currents at various rotation angles about the y-axis. The homogenous magnetic field B_x is fixed along the x-axis with a value of $B_x = 1$ T; the supply current is $I_{C1} = 10$ mA.

4. Measurement Errors

4.1. Angular position measurement error

The angular position of an axis is determined by measuring the direction of the magnetic field generated by a small permanent magnet glued at the end of the axis, Figure 4. The sensor is sensitive to the B_x and B_y components of the magnetic field parallel to its surface. The B_z sensitivity element will be used for the purpose of tilt compensation. Ideally the magnet should be parallel to the sensor chip and centered above it [2, 10].

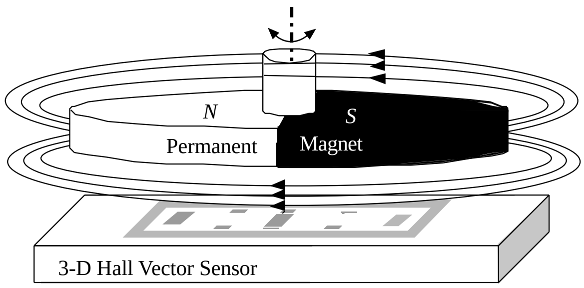

Figure 4. Working principle of the angular position sensor.

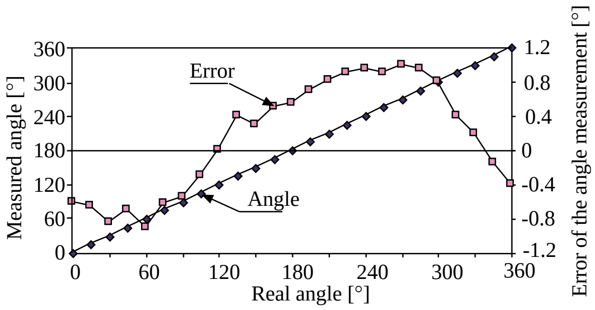

Figure 5. Error of the angle measurement—error between measured and actual angle. The maximum error measured for a rotation of 360° is ± 1°.

By rotating the axis 360°, and with the permanent magnet fixed in position, two sine curves, phase shifted by 90°, are obtained at the outputs of the sensor [2]. The graph shown in Figure 5 shows the measured angle as a function of the real angle. The second curve on the same graph shows the error of measurement. A precision of ±1° is obtained for one complete rotation.

If we start studying the error of the angle measurement, from the graph at first approximation, we can determine the change tendency of the error for a rotation of 360°. The relation is $Err \sim -\sin\,(\phi_{real} + \pi/3)$, where ϕ_{real} is the real angle, as used in Figure 5.

4.2. Misalignment tilt-error measurement

The integrated orthogonal sensor, sensitive to the B_z component, is used to compensate the relative misalignment, angle α, between the sensor and the magnet. This sensitive element, combined with those elements sensitive to B_x or B_y can be used to measure the tilt of the magnet above the sensor. In this paper measure of sensor tilt is presented only. The permanent magnet is fixed: it does not move along the z axis, only rotation about z. In order to characterize the tilt sensitivity of the sensor, the device was rotated around x-axis (tilt axis of the sensor) in a homogeneous magnetic field $B = 1$ T (see Figure 6). The inevitable channel offset is compensated beforehand. Next, sensitivity to rotation about the x and y axes was determined by using the $y - z$and the $x - z$sensitive devices, respectively. Figure 7 shows the measurements of the tilt for x rotation; the y-rotation measured results are almost the same. A precision of about of ± 3° is obtained for the tilt angle measurement.

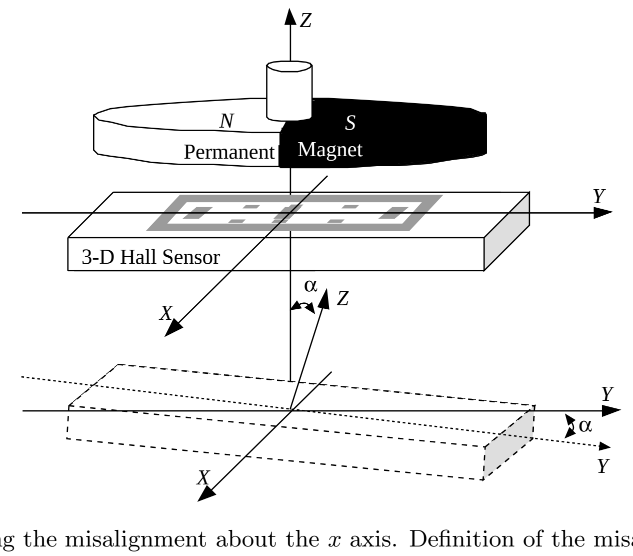

Figure 6. Scheme describing the misalignment about the x axis. Definition of the misalignment about the y axis is equivalent.

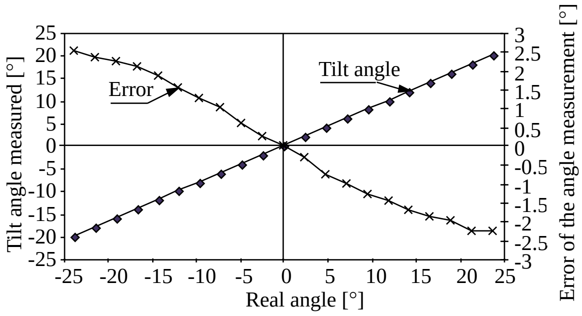

Figure 7. Tilt measurement for x rotations. The sensor is rotated around x axis in a homogeneous field of 1 T.

5. Conclusions

The angular position measurement results presented are for a 3-D Hall effect transducer. This is a fully integrated 3-D magnetic field sensor that has a precision of $\pm 1^\circ$ for a complete rotation around the z-axis. So as to compensate the misalignment of a magnet above the sensor, the z-axis sensor is introduced. The angle measurements at this moment were almost performed with the 2-D Hall sensors. With help of the B_z and B_y component sensors, tilt about the x-axis is detected and compensated to a precision of $\pm 3^\circ$, including calibration. The results presented here make clear the need for further work to improve precision and accuracy at all orientations.

Acknowledgements

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