Novel Magnetic Displacement Sensors

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Abstract—We describe a new magnetic displacement sensor, which measures the position of a magnet along a line or in the plane. The sensor is inherently non-sensitive to the magnet movement along the third axis, temperature variations and aging, and does not require calibration. This is achieved by transforming a translation of the magnet into a rotation of a magnetic field, and by measuring the direction of the magnetic field rather than its strength. The direction of the magnetic field is then measured by two-axis Hall sensors.

Index Terms—Hall sensor, magnetic position sensor, contact-less position measurement.

I. INTRODUCTION

POSITION sensors encompass a wide range of sensors, switches and technologies that are used to determine the position, speed or direction of movement of a given target. Linear position devices include capacitive, eddy current, fiber optic, Hall effect, inductive, magneto-resistive, optical triangulation, photoelectric, ultrasonic, and variable resistance technology sensors.

Hall effect magnetic position sensors are the preferred solution for many applications, since they are contact-less, small in size, robust, reliable, not sensitive to harsh and polluted environmental conditions, and low-cost.

But the known Hall effect based position sensors are limited in accuracy by offset, noise, temperature dependence and ageing effects. This is the reason why traditionally they are mainly used as contact-less switches detecting just the presence of a magnet or magnetized body and not as linear sensing devices. Through the co-integration of Hall element(s) and electronics on the same chip, offset and 1/f noise can be effectively reduced by the spinning current technique. However, to compensate such a position sensor for drift with temperature and ageing effects of the Hall sensor and the magnet, generally more involved and expensive treatment is required, such as calibration and digital data processing.

Another important drawback of magnetic position sensors is the strongly non-linear decrease of the magnetic field strength with distance from the field source, unless a very big and costly structure is implemented. For a simple small magnet the field decreases with $1/r^3$ with the distance $r$. Here again the raw output signal must be linearized by data processing.

In this paper we present an elegant solution, which allows to virtually eliminate all above drawbacks, namely temperature drift, ageing effects and non-linearity at the same time, without adding new ones.

Essentially, the good properties of our sensor are due to the fact that we measure the rotation of the field of a small magnet and not the field strength as all known Hall position sensors do.

II. MEASUREMENT PRINCIPLE

A. Single Axis Displacement Sensor

The concept of the present magnetic position sensor, which is based on our recent patent application [1], is shown in Fig. 1. The sensor consists of two parts: a cylindrical permanent magnet, and a two-axis Hall sensor. The two parts can translatory move with respect to each other, along the three mutually perpendicular axes $x$, $y$, $z$. We assume that the substrate is parallel with a $(x, y)$ plane. The permanent magnet is magnetized along its rotational axis, which is positioned perpendicularly with respect to the substrate (z-direction).

When the magnet moves along the x-axis, the component of the magnetic field parallel with the $(x, y)$ plane, seen by the Hall
sensor, rotates and changes strength (Fig. 2). Of course, field rotation also happens for a movement along the y-axis, hence, for a single-axis displacement sensor Y has to be kept constant. Interestingly, if the magnet moves along its axis (z), the magnetic field direction in the (x, y) plane does not change. This is because the cylindrical magnet produces a radial magnetic field in any (x, y) plane not identical to its plane of symmetry. This stays so in spite of eventual changes of the strength of the magnetic field due to temperature or ageing effects.

Both of these curves look quite non-linear, but nevertheless, a very linear position information can be obtained from them. For this it is only necessary to build the ratio $V_x/V_y$ as shown in Fig. 4. This figure also gives the calculated error between the mechanically measured position and the position obtained from the magnetic sensor. We can see, that the linear range is limited to about 2.5mm. However, within this range the absolute error is less than 25µm. This corresponds to 1% absolute accuracy within this range.

The question is now: How do we obtain accurate displacement information for the magnet from this field rotation?

To solve this, we first have a look at the signals measured by the sensor as plotted in Fig. 3. As the magnet moves, the field component in motion direction $B_x$ is first negative, then crosses zero at center position and increases to positive values. For both, far negative and far positive positions, the field becomes weaker as the distance between magnet and sensor increases. The $B_y$ field component is always positive with a maximum about zero position.

To understand this result, we now give a short analytical explanation.

In our approach we use two-axis Hall sensors for the measurement of $B_x$ and $B_y$. They measure the in-plane components $B_x$ and $B_y$ of the magnetic field vector $B$. The corresponding Hall output voltages are $V_x$ and $V_y$. The sensors are very linear in the used magnetic field range, so that

$$V_x = S \cdot B_x, \quad V_y = S \cdot B_y$$

(1)

where $S$ is the sensor sensitivity, $S \neq B$.

From the similarity of the corresponding triangles in Fig. 5 we deduce the following:

$$\frac{B_x}{B_y} = \frac{X}{Y}$$

(2)

Fig. 2 Top view of the single-axis displacement sensor. The magnet moves parallel with the x-axis and the xy component of the magnetic field at the place of the sensor changes strength and rotates.

Fig. 3 The two sensor output voltages as obtained with a passing by of the cylindrical magnet.

Fig. 4 Linear displacement signal and position error obtained by division of the two sensor output voltages.

Fig. 5 The top view of the displacement sensor helps us to establish the relationship between the measured magnetic field components and the position of sensor and magnet.
On the other hand:

\[
\frac{B_X}{B_Y} = \frac{V_X}{V_Y} = \tan(\alpha) \quad (3)
\]

Then we can calculate from the above equations:

\[
X = Y \cdot \tan(\alpha) \quad (4)
\]

Here \(\tan(\alpha)\) is obtained by calculating the ratio of the two Hall voltages Eq. (3). These values are independent of the absolute field strength and also of temperature effects and ageing as long as these effects are similar for both sensor axes.

This concept allows measuring a position along an axis with the great advantage of virtual immunity to the sensor and magnet tolerances as well as to temperature and aging effects. Moreover, the measurement result is theoretically independent to the mutual distance between the magnet and the Hall sensor along the third axis (z).

**B. Two Axis Displacement**

After the application of a two-axis Hall sensor for single-axis displacement sensing, we now extend the principle to two-axis displacement sensing. Whereas up to now we were using the magnetic field direction in one point to determine one position coordinate (x) of the magnet, we now want to determine the coordinates of the magnet in the plane (x and y) and we therefore need to measure the magnetic field direction in two points. This can be realized by using a first and a second two-axis Hall sensor, as shown in Fig. 6.

Again, when the magnet moves in the (x, y) plane, the components of the magnetic field parallel with this plane, seen by the two Hall sensors \((B_1, B_2)\), rotate.

Now we will develop the equations defining the magnet position with respect to the sensors. Let us assume that two such sensors are placed at a distance A from each other, Fig. 7.

**III. EXPERIMENTAL SETUP**

For the experimental setup we used two-axis Hall sensors 2D-VH-11 of SENTRON AG [2]. Such sensors are based on vertical Hall devices described in [3] and they are sensitive parallel with the chip surface. The angular error between the two sensor axes is smaller than 0.1°.
Two such sensors were mounted on a ceramic substrate at a distance of $A=2\text{mm}$. A samarium-cobalt cylindrical permanent magnet with a diameter of $6\text{mm}$ and a length of $2.5\text{mm}$ was placed at $Y=3\text{mm}$ from a line through the sensors and at $z=0.5\text{mm}$ above them.

The Hall elements are biased with the constant voltage of $5\text{V}$. Except of cancelling offset voltages, no adjustments or calibrations were made. The Hall output voltages are amplified using conventional integrated differential amplifiers and then converted into digital signals. The directional tangent functions (6), and the magnet position co-ordinates (7), are calculated using a microprocessor.

The position sensor was mounted on precise micrometric translation stages (see Fig. 8).

All measurements were performed at room temperature, without any temperature stabilization measures.

Fig. 8 Photograph of the measurement and test setup. The magnetic position sensor is tested with reference to precise micrometric translation stages. The test setup allows to place the sensor with high precision on $x$, $y$ and $z$ coordinates with an error of less than $2\mu\text{m}$.
IV. SIMULATION OF LIMITATIONS DUE TO NOISE

Before we start with the actual displacement measurements, we want to quantify the limits of measurement accuracy given by noise. For this reason we have established a simulation model of our magnet and sensors where we can calculate the influence of sensor noise on the displacement value (Fig. 9). We measured the sensor noise before to a value of ±10 μT over the frequency range from 0.01 to 100 Hz.

The y and z coordinates for which we simulated a displacement in x-direction are given in Fig. 10. The distances are from 0.5 mm to 1.5 mm in vertical z direction and from –1.1 mm to +1.1 mm from the magnet edge in y-direction.

Now we performed a simulation for displacement in x-direction and we calculated the uncertainty at each position due to the sensor noise. According to (7) we can quantify this error for the varying coordinate X as well as for the constant coordinate Y.

Fig. 11 shows such displacement error simulation result for Y. The error is smallest in the center, where the signal to noise ratio is highest and increases towards the outside.

The sensor noise causes a corresponding X-position error of ±0.75 μm, and in Y-position error of: ±2 μm. (for a movement in x-direction). This corresponds to the maximum obtainable accuracy of such a position sensor. In order to further increase the accuracy, the magnetic field has to be increased, for example by using a bigger magnet or a different magnet material.

V. EXPERIMENTAL RESULTS

A first measurement result of this setup was already given in Fig. 3, showing the measured output signals of one of the Hall sensors for a displacement of the magnet along the x-axis.

We shall now test the equation (7) of the position sensor system. For a displacement along any one of the three axes x, y and z at a time and by keeping the other two coordinates constant, we should once receive a signal proportional to X, once proportional to Y and then it should be constant if we move along z. To investigate the obtainable accuracy of the
sensor, we then plot for each of the three measurements the difference between the measured position and the mechanical reference position in µm.

Fig. 12 shows the calculated X and Y position for a displacement of ±2mm around zero on the x-axis. We notice that the measured X value is very linear with the position and that the measured Y value is nearly constant.

![Movement in X-direction (Y = 3000um, Z = 500um)](image)

Fig. 12 Position signals X and Y calculated from the Hall sensor voltages for travel along x-axis

In Fig. 13 we give the calculated remaining error between the measured values and the reference position of the translation stages.

![Measurement errors for movement in X-direction (Y = 3000um, Z = 500um)](image)

Fig. 13 Position error between Hall sensor measurement and mechanical reference for travel along x-axis

The error on X is less than 10 µm (0.5% full scale) and on Y about 40 µm (2% full scale). However, tests with other magnet samples have shown that these errors arise from non-uniformity in the permanent magnetic material and not from the sensor inaccuracy.

In the next, step we investigate the output signals for a movement along y-axis. Fig. 14 shows the position data calculated from the sensor outputs. It can be noticed, similar to the first case, that the calculated position for the movement (Y) is very linear, whereas the other value (X) is nearly constant.

![Movement in Y-direction (X = 0um, Z = 500um)](image)

Fig. 14 Position signals X and Y calculated from the Hall sensor voltages for travel along y-axis

When we now again plot the errors between measured and mechanical position (Fig. 15), we can see, that the accuracy of the measured X position is about ±5 µm (±0.5%) and for Y about ±10 µm (±1%) in the range from 1..3mm. For larger distances both errors increase due to the strongly decreasing field, causing the Hall voltages to become very small.

The experimental setup is optimized for a Y-position of 2..3 mm and shows up to Y = 3.8 mm an accuracy of 1% for displacement along x.

![Measurement errors for movement in Y-direction (X = 0um, Z = 500um)](image)

Fig. 15 Position error between Hall sensor measurement and mechanical reference for travel along y-axis

The last case to investigate is whether the position sensor is really insensitive to a movement of the magnet along its axis (z) or not. Fig. 16 shows that for this case indeed the output signals x-position and y-position stay virtually constant.
Movement in Z-direction (Y = 3000um, X = 0um)

For the z-position range, from z = 0.5..2mm, we find an x-position error of ±10 µm, which corresponds to ±0.5% of ±1mm and a y-position error of ±10 µm, which also corresponds to ±0.5% of ±1mm (Fig. 17).

Here again, it can be observed that the amplitude of the sensor signals and so the signal quality decreases fast with increasing Z-distance.

Fig. 16 Position signals X and Y calculated from the Hall sensor voltages for travel along z-axis

VI. ANALOG INTEGRATED DISPLACEMENT SENSOR

Considering equations (3) and (6,7) we notice, that for the single-axis, and even more for the two-axis displacement sensor, several ratios have to be calculated to obtain a signal proportional to the displacement value. This can be performed by a microcontroller or any other advanced digital signal treatment. Those components increase the system price and the arithmetic operations are often very time consuming.

For this reason we have developed a system architecture which allows to perform the ratio of the two Hall voltages Vx and Vy in an analog way already on the chip-level.

Fig. 18 shows a circuit schematic for a magnetic displacement sensor based on a two-axis Hall sensor which directly outputs a voltage proportional to the ratio of the two perpendicular magnetic field components.

The circuit contains a Hall element H1 for measuring the component By and a Hall element H2 for measuring the component Bx. The output voltage of H1 is amplified by Op1 and the one of H2 by Op2. Op3 controls the bias current through H1 and H2, in such a way, that

\[ V_Y = V_{ref} \quad \text{for} \quad R_1 = R_2 \]

with \( V_{ref} \) as a predefined reference voltage.

On the other Hand, the Hall voltages are given as product of biasing current, sensitivity and magnetic field:

\[ V_{out} = V_X = S_{ix} \cdot I_X \cdot B_X \quad \text{and} \quad V_Y = S_{iy} \cdot I_Y \cdot B_Y \]

Since the two Hall elements are similar and biased in parallel by the same voltage, we may write

\[ I_X = I_Y = I \quad \text{and} \quad S_{ix} = S_{iy} = S_I \]

This finally leads us to an expression of the output voltage

\[ V_{out} = V_{ref} \cdot B_X / B_Y \]

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The division of the measured components of the magnetic field takes place analogously because with this circuit the current flowing through H2 is proportional to the Hall voltage of H1. Therefore the circuit delivers an output signal Vout, which is proportional to the ratio Bx/By.

The feed-back loop for the supply current control is implemented via a PI controller, so that the control loop is at the same time fast and stable. First experimental results of this architecture for the application as displacement sensor will be available in early 2003.
VII. SOME APPLICATIONS

A. Contactless Adjustment Sensor for Machinery

The magnetic displacement sensor is a very robust and cheap sensor to adjust parts of machinery in a plane without requiring expensive and pollution-sensitive optical systems.

B. Thickness Monitoring

In this application the magnetic displacement sensor monitors the thickness of items like sheets or wires passing by during production. The advantage of using a magnetic device here, is that it is very insensitive to dust and fibers and that it cannot be destroyed like mechanical sensors by a sudden stroke.

C. Long Range Incremental Displacement Sensor

Here the magnetic displacement sensor is used as part of a linear position encoder for displacement ranges much larger than sensor or magnet. A plurality of equally spaced sensors is arranged in a line and a magnet is attached to the part moving parallel to the line. Our measurements showed that the signal of one sensor is very linear in a range of about 1.5 times the magnet diameter. This means that for a magnet of 6mm diameter on sensor every 9mm is sufficient to obtain an accurate displacement value over the entire sensor array. The decision which sensor has the valid signal can be obtained by a very simple comparator operation.

D. Vibration Sensor

A typical application for displacement sensors is to detect slightly increased vibration of defective rotating machinery before failure. For this application the displacement sensor can be used as a small module in combination with a small magnet which is mounted on a flexible suspension. Suspension and magnet are matched to meet the requirements of vibration amplitude and frequency. Such a solution can even be imagined as a totally self contained micro-electro-mechanical system (MEMS).

The absolute accuracy can be increased by calibration. To this end, we may simply use a look-up table in a micro controller. By doing so, the accuracy will be limited by the system noise and offset instability.

To increase the mutual alignment and the precision of the distance A between the two two-axis Hall sensors, they can both be integrated on the same silicon chip. This becomes possible with the technology of our new integrated CMOS Hall angular position sensor [4]. Moreover, by integration with analog electronics, the division of the two Hall voltages can already be performed on the chip, so that a linear displacement signal is generated.

REFERENCES