Trough-shaft contactless magnetic sensor with a stroke up to 360°

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1. Introduction

Magnetic position sensors have several advantages which make them attractive for automotive applications: they are contactless (there is no mechanical wear-out), insensitive to dirt, feature reduced sensitivity to temperature and geometric tolerances and are low cost. Recently developed angular position sensors use probes which measure the angle of the magnetic field generated by a diametrically magnetized magnet [1]. The magnet in these sensors is mounted at the end of a rotating shaft and the probe measures two magnetic field components in the plane parallel to the magnet and on the rotation axis of the shaft, thus obtaining the field direction. However, this sensor configuration is not possible if a through-shaft is required by the application. For this reason, another sensor configuration is studied, with a probe installed next to the magnet. In the following text, first the sensor principle is explained. The basic design considerations are then explained through examples. Magnetizing of the magnet for such a sensor is investigated. Four prototypes for automotive applications are presented and measurement results are given.Tolerances to geometrical faults are also discussed.

2. Sensor principle

A new generation of Hall sensors, based on the measurement of the magnetic field direction, is shown in Figure 1. These sensors have some advantages over classical Hall sensors measuring the field strength: no need to compensate for magnet over temperature, better tolerances, simple structure.

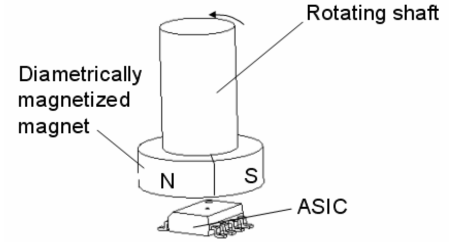

Figure 1: Hall sensor measuring the direction of the magnetic field

In the proposed sensor solution [2] the ASIC for magnetic field measurement is installed next to a diametrically magnetized magnet ring (Figure 2), and, in this case, the angle of the magnetic field does not follow the rotational angle of the shaft. To solve this problem, we should consider the magnetic field components separately.

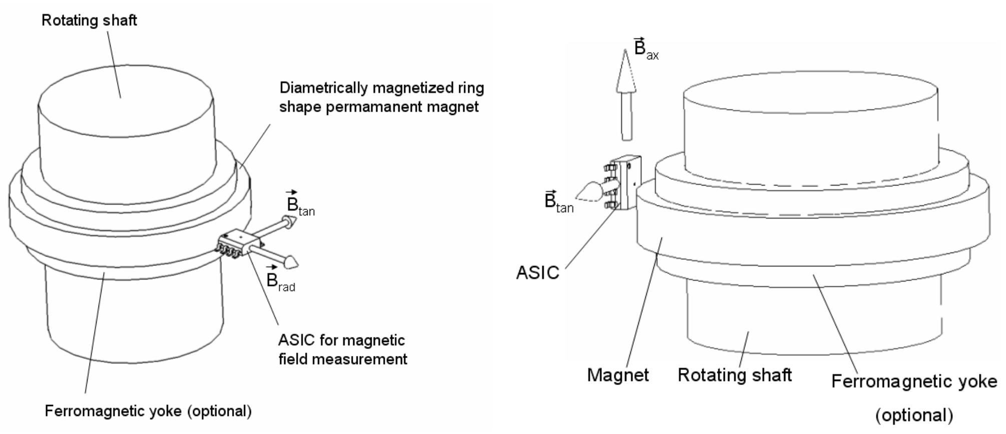

Figure 2: Through shaft sensor overview

The solution for magnetic induction outside a diametrically magnetized infinitely long cylinder can be found in literature [3]. The following analytical solution for radial and tangetical field component is obtained:

$B_{rad} = B_{max} \cos\varphi$ $B_{tan} = B_{max} \sin\varphi$, where B_{max} depends on radius as $\frac{1}{r^2}$.

Two sinusoidal signals with 90° phase shifts are obtained. For diametrically magnetized cylinders with finite length, one must solve the field equations numerically. The obtained solutions are, again, two sine signals with 90° phase shift between them (Figure 3), and their amplitude ratio depends on the magnet dimensions.

$$B_{rad} = B_{rad\,max} \cos\varphi\,; \qquad B_{tan} = B_{tan\,max} \sin\varphi$$

where: B_{rad} - radial induction

B_{tan} - tangential induction

Ring magnet can be represented as a difference between two cylindrical magnets with finite length, so the solution for its magnetic field will have the same form. An example is given in Figure 3, the results are obtained using a boundary element software [4].

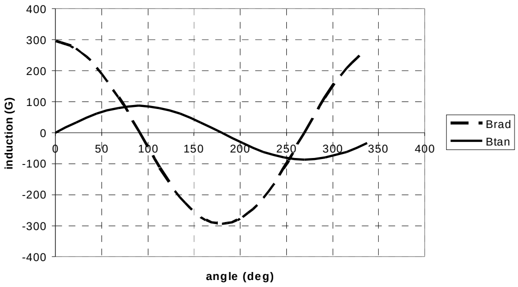

Figure 3: Radial and tangential induction components - simulation results

In order to compute the angle of rotation, two different amplification ratio are applied to the two signal components before computation of the angle. Then it is possible to obtain the rotational angle by computing the arc tangent so we have:

$$\varphi = \mathrm{ATAN}\left(\frac{G1}{G2}\frac{B_{rad}}{B_{tan}}\right)$$

We notice that the angle obtained does not depend on Br of the magnet, therefore there is no need for temperature compensation.

Angle computing block is illustrated in Figure 4, G1 being in general case different from G2.

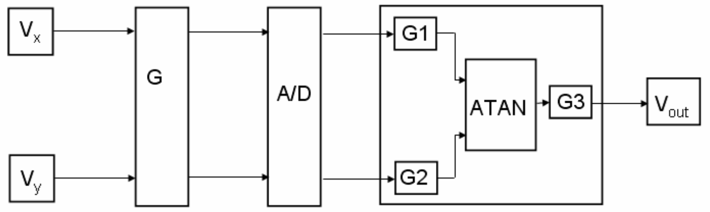

Figure 4: Angle computing block

Another possible configuration is to use axial and tangential field component (Figure 2). It could be useful for some embodiments needing the probe close to the magnet.

3. Practical realization

3.1. Sensor design considerations

The "goal" is to have enough magnetic field at each point along the measured stroke and for the full temperature range. For each design, magnet dimensions (inner and outer diameter, heigth) and distance probe-magnet should be determined. Several parameters should be taken into account: overall sensor size limits, magnet type, probe, production tolerances.

In Figure 5 a parametric analysis through 3D simulations is shown for a ring magnet with Br=0.6 T and with ID = 10 mm. OD, height of the magnet and distance probe-magnet are taken as variable parameters. Amplitudes of radial and tangential components are given for each simulated case.

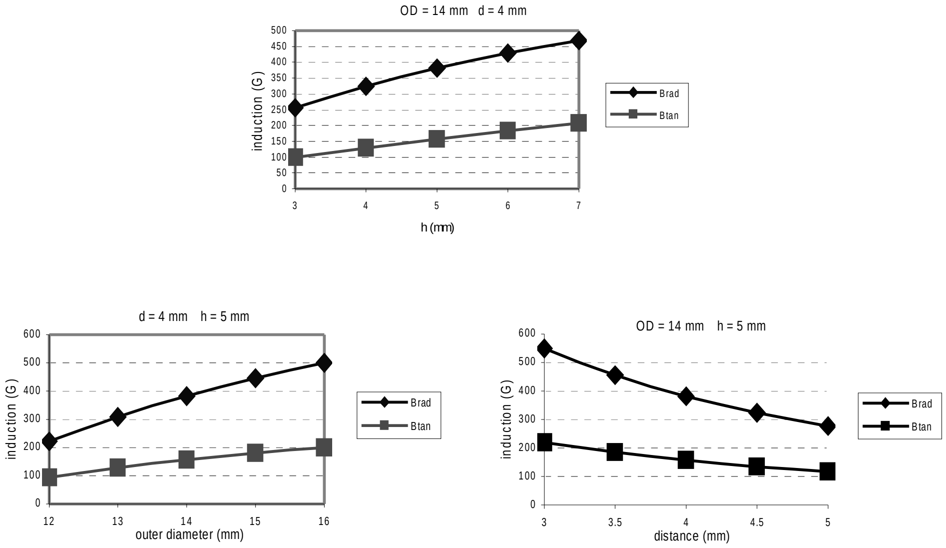

Figure 5: Parametric analysis of the sensor design (simulations)

One can see from the above calculation that the magnet thickness is a very important parameter, but influence of the height is also significant. Both parameters influence the amplitudes of radial and tangential component of the induction so their ratio.

The use of a ferromagnetic yoke inside the magnet is possible but it will mainly increase the amplitude of the radial component, and so the ratio between the two components will be larger.

Sensor design and practical realization will be illustrated through examples of prototypes below.

3.2. Examples of prototypes

All prototypes are made with bonded NdFeB magnet having approximately 0.7 T remanent induction, knowing that this value is higher than necessary for most applications. The probe used is MLX90316 [5].

3.2.1 Steering angle sensor

First prototype is for a steering column application which requires a trough-hole with 30 mm diameter for construction reasons. We selected a 32 mm inner diameter magnet, mounted on a ferromagnetic yoke. 36 mm outer dimameter and 5 mm height are imposed by magnet robustness/cost trade-off.

The prototype and measurement results are shown in Figure 6 below.

Figure 6: Prototype for steering application with output voltage and linearity for 359° stroke

The amplitudes of radial and tangential component are 470 and 115 G respectively and a non-linearity of about 0.4% on 359° stroke is achieved. This sensor can be used for multi-turn measurements as it is shown in the following example. This sensor has been tested in temperature from -38 up to 125 ° C. The result is given in Figure 7. The non linearity over the complete temperature range is held within 0.8% of the full stroke.

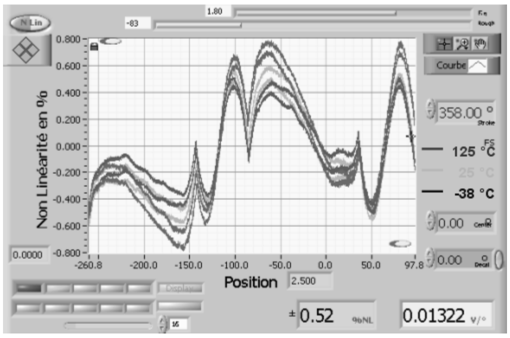

Figure 7: Steering sensor – non-linearity obtained and temperature test

3.2.2 Multiturn application of the steering sensor

The magnetic part of the sensor is the same as in the previous one. Mechanical transmission system divides the rotational angle of the outer circle by 3. An epicyclic gear train is used in order to reduce the size of the device. The mechanical principle, the overview of the transmission mechanism and the measurement result for 1077° stroke are given in Figure 8. 2 out of 3 arms are elastic in order to avoid mechanical play which would lead to hysteresis in the behaviour of the sensor.

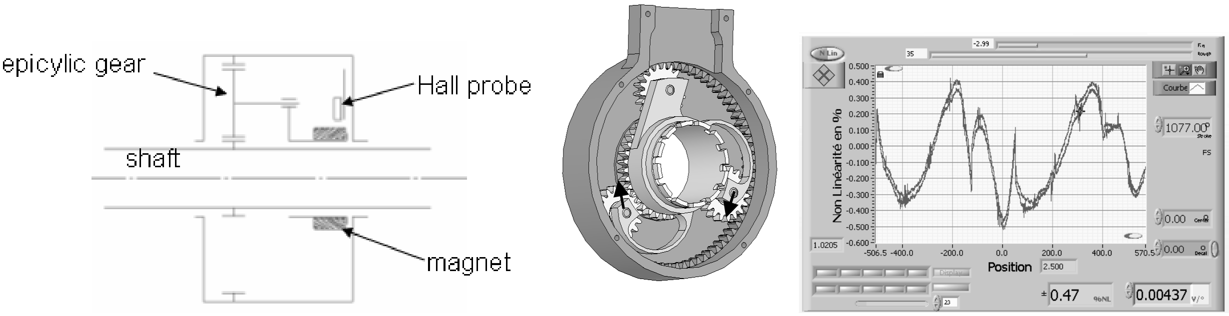

Figure 8: Mechanical scheme and overview of the transmission mechanism

3.2.3. Small sensor

A smaller prototype has been made with an outer diameter limited to 30 mm. The overview of this design and the measurement result for 356° stroke are shown in Figure 9. Magnet dimensions are: OD = 12 mm, ID = 8 mm, h = 5 mm.

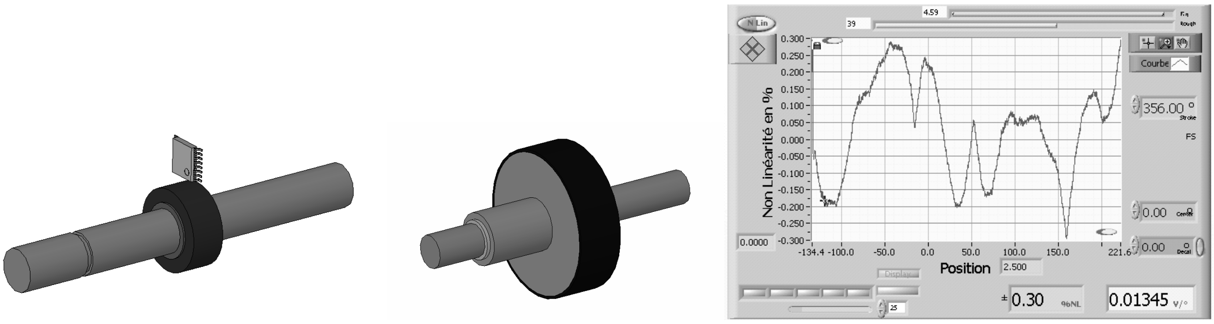

Figure 9: Inside and outside view of the sensor prototype and measurement result

A 0.3% non-linearity is obtained and this design could replace potentiometers in some applications. This sensor could be used in several automotive applications, such as suspension, fuel level, ETC or pedal sensor.

3.2.4. Tiny sensor

An even smaller prototype has been made as a possibility to replace small size potentiometers in some applications. Magnet dimensions are: OD = 7 mm, ID = 5.5 mm, h = 3 mm. In Figure 10 dimensions of the prototype and measurement results are given.

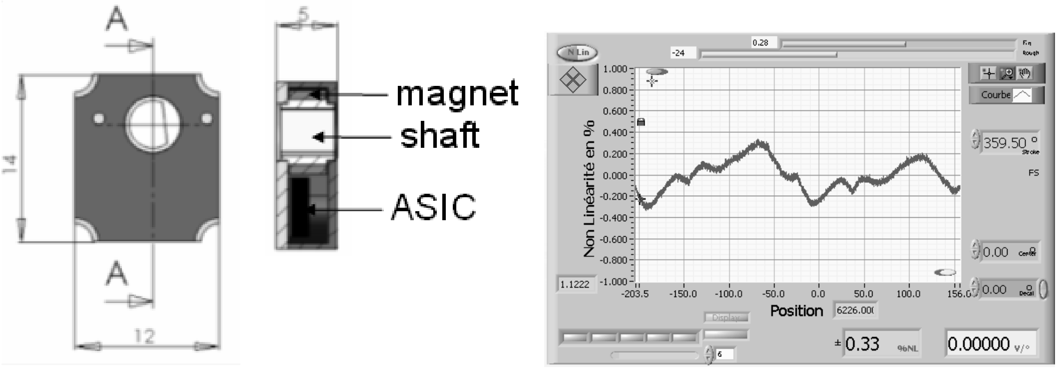

Figure 10: "Very" small sensor: overview, dimensions and measurement result

A 0.33% non-linearity on 359.5° stroke is obtained, thus even small potentiometers can be replaced by this type of sensor.

4. Magnetizing

In most cases, practical measurement with a diametrically magnetized ring magnet exhibits significant non-linearity in the computed angle. The reason for this is found in the magnetizing process: the magnetizing field is refracted on a magnet surface, due to the boundary conditions [3]. In Figure 11 this effect is shown both in simulation result and in measured Brad and Btan. This effect is difficult to avoid, but its influence can be significantly decreased if it is taken into account in the angle computing block (Figure 4), thus the processing should be adapted for each sensor design.

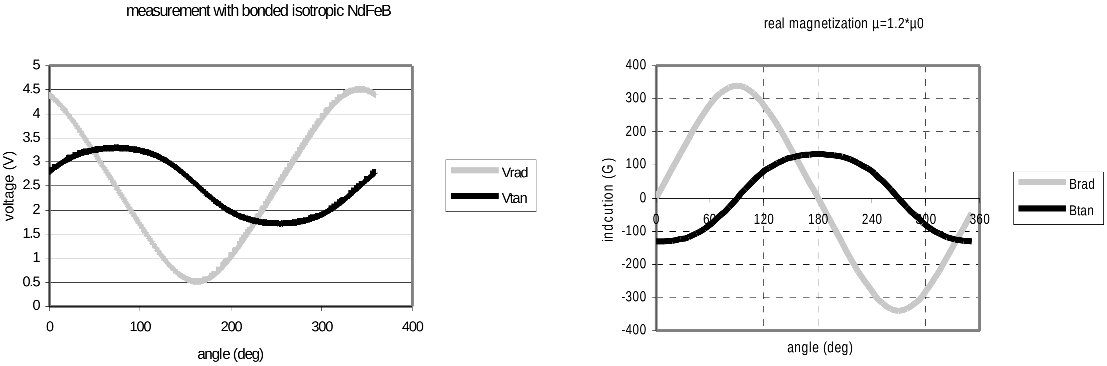

Figure 11: Real magnetization: measurement versus simulation

5. Tolerances

Three kinds of geometrical faults were tested: radial, axial and tangential shift. The measurement result for a magnet with 1.2 T remanent induction and OD = 30 mm, ID = 26 mm, h = 5 mm are given in Figure 12.

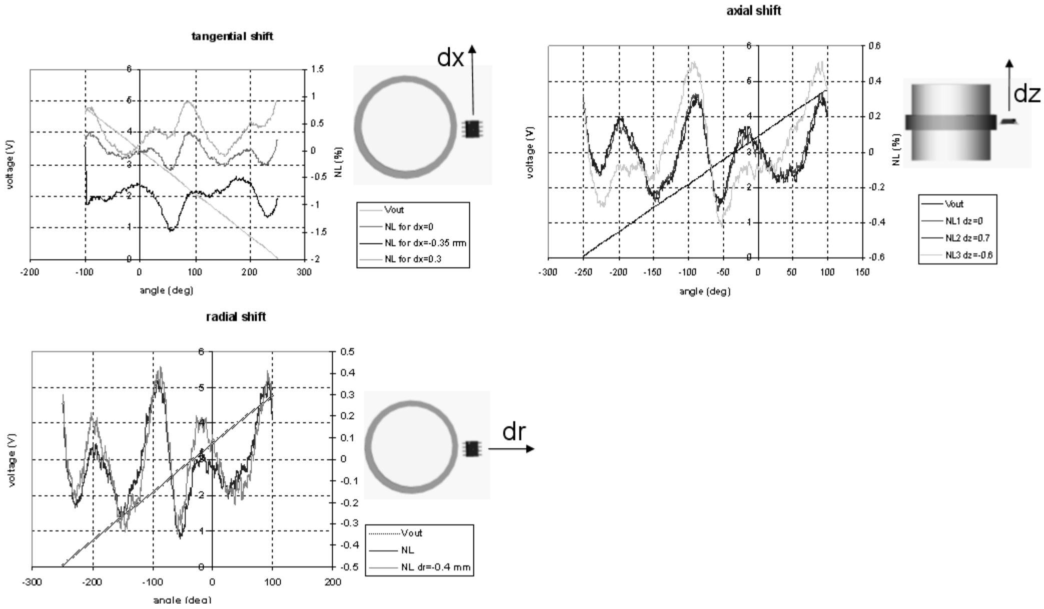

Figure 12: Geometrical faults - measurement results

One can notice that the only critical geometrical error is the tangential shift, and it should be carefully considered depending on tolerances for each design. This error can be minimized both by fabrication (greater stiffness) and by design (increasing the sensor diameter).

6. Conclusion

A new 360° through-shaft low cost magnetic sensor is proposed. Its performances are evaluated through simulation and measurement results.

Several prototypes having different sizes have been realized and good overall sensor performance (0.3-0.4 % non-linearity on 360° stroke) is achieved. As the measurement principle is independent of the magnetic field amplitude (as long as it is sufficient for the ASIC), this sensor can use all types of magnets: ferrites, SmCo, NdFeB. This sensor can fit various automotive applications having medium to large angular strokes (from several dozens up to 360 degrees), such as steering, transmission, fuel level, pedal or ETC sensor. Further improvements can be made on magnetizing in order to gain in accuracy. The tolerances to geometrical errors are intrinsically very good.

7. Literature

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