Two-axis inclination measurement system based on a planar flux-gate sensor

Luigi Rovati and Stefano Cattini
Department of Information Engineering, University of Modena and Reggio Emilia
Via Vignolese 905, I-41100, Modena, Italy
Email: luigi.rovati@unimore.it

Abstract—A tilt-sensitive measuring system exploiting a flux-gate sensor is described. The sensing configuration has been investigated using an electromagnetic modelling software first. Then, the prototype characterization has shown a system sensitivity up to 2.3491 V/° and an Integral Non Linearity (INL) down to 1%.

I. INTRODUCTION

Tilt angle measurements attracted considerable interest in several metrological areas ranging from earth science (e.g., geophysics and geodesy), engineering (e.g., architecture and building engineering, mechanics, robotics and automation in general) to entertainment (console joystick).

Depending on sensitivity, dynamic range and cost, several systems have been realized exploiting different measurement models [1]–[3]. Recently, a magnetic tilt-measurement system exploiting a Hall sensor has been proposed [4].

Allowing contactless probing, magnetic sensing may lead to higher reliability and MTTF (Mean Time To Failure). Among magnetic sensors operating at room temperature, flux-gates are the best choice in applications requiring high resolution, low-cost, and low temperature coefficient (less than 30 ppm/°C).

We report what is to our knowledge the first tilt measurement system based on a planar flux-gate sensor. The proposed tilt-measuring system (TMS) exploits a PCB planar flux-gate measurement system (FMS) developed in our laboratory [5].

In the present paper, we propose to exploit two magnets in order to induce a tilt-related magnetic field into the flux-gate sensor core. Preliminary analyses, aimed at identify suitable system topology, have been performed exploiting the simulation program Vizimag® [6]. After a concise description of the main flux-gate performances, two measurement topologies are introduced and analyzed. Then, preliminary calibration curves of the realized prototype are reported and discussed.

II. MATERIALS AND SYSTEM TOPOLOGY SELECTION

A. Flux-Gate Sensor Performance

Flux-gate sensors are vector magnetometers, thus sensitive to the axial component of the magnetic field along one or more sensitive axis/axes ($B_{ax}$).

Measurements were performed exploiting the PCB flux-gate previously reported by Baschirotto et al [7], and depicted in Figure 1. It consists of an excitation coil and four sensing coils. The planar excitation coil is characterized by 30 µm thickness, 30 turns and 400 µm pitch. The ferromagnetic core is shaped as a cross in order to make the device sensitive to the two components of a magnetic field coplanar with the PCB. The ferromagnetic material core is a 25 µm thick lamina of the amorphous alloy Vitrovac®6025 (Vacuumschmelze Hanau, Germany). This material was chosen because of its extremely high relative permeability and low losses. For each component of the magnetic field ($x$ and $y$ axes) the output voltage is obtained from the relative two sensing coils placed in differential configuration, having 17 µm thickness, 21 turns and 400 µm pitch. As shown in figure 1(b), the excitation and sensing coils are realized on two different metal layers of the multilayer PCB structure, at a distance of about 50 µm from each other. The thin x-shaped ferromagnetic core is glued to the so obtained PCB coils.

As shown, the device exhibits two sensible axes, thus allowing the realization of a two-axis tilt measurement system. For each sensible axis, the sensitivity ($S_{FMS}$) of the FMS can be easily set from 13.3 mV/µT to 104.9 mV/µT with nonlinearity ranging from 0.17% to 0.38% of the measuring range, whereas the corresponding dynamic range varies from ±301 µT to ±38 µT.

The system uncertainty and the noise field spectral density have been estimated in 12.2 nT and 10 nT/√Hz respectively.

B. Selection of the System Topology

To measure a tilt exploiting a magnetic field sensor, different tilts should induce different $B_{ax}$ into the sensing axes. During the topology analysis process, the following constraints have been considered: low cost, effective tilt to field conversion and low mechanical wearing for the sensing device. Moreover, the TMS has to allow the two axes tilt measurements.

Nevertheless, given the symmetry of the problem and in order to reduce the test setup complexity, all the reported activities have been performed considering one sensing axis only.

As stated before, preliminary simulation analyses have been performed exploiting the electromagnetic modelling software Vizimag®. This software allows simulating 2D arbitrary-shaped objects and setting their magnetic properties (magnetic permeability $\mu$, Residual Magnetism $B_r$ and other physical quantities). It provides the 2D analysis and simulation of field lines and flux density in a graphical and matricial output format. As a result, the tilt-to-field conversion efficiency ($c.e.$)
has been estimated in terms of magnetic field induced along the \( x \)-sensing-axis. Hence, exploiting the output matrix, the mean magnetic filed intensity along the flux-gate \( x \)-sensing-axis has been computed as:

\[
B_{ax\text{-mean}} = \frac{1}{2} \int_{-x_a}^{x_a} \vec{B} \cdot \hat{x} \, dx ,
\]

where \( \hat{x} \) is the \( x \)-axis versor, \( -x_a \) and \( x_a \) are the start and stop coordinates of the flux-gate core along the \( x \)-axis and \( \cdot \) represents the scalar product. The \( c.e. \) has been assessed by the analysis of the normalized mean axial field (\( B_{NORM} \)):

\[
B_{NORM} = \frac{B_{ax\text{-mean}}}{B_{r\text{-TOT}}} ,
\]

where:

\[
B_{r\text{-TOT}} = \sum_{i=1}^{N} B_{r-i} ,
\]

\( N \) is the number of the exploited magnet/s and \( B_{r-i} \) is the residual magnetism of the \( i \)-th magnet.

Several topologies have been considered, thus testing different arrangements, \( B_r \), and aspect ratios. Nevertheless, in order to realize a low-cost system, only typical commercial-magnet shapes have been considered. As a results, the investigated topology exploits arc shaped (PC hard disk like) or rectangular right prism magnets only.

As an example, Figure 2 shows an arrangement (\( Sim_1 \)) based on two arc-shaped magnets (approx 120° semicircular) and few non-ferromagnetic elements aimed at realize a sort of flattened ellipsoid. As shown in Figure 2, the PCB flux-gate sensor was placed in the axis-origin and the rotation fulcrum lay along the \( x \) axis just beyond \( x_a \).

Notice as in \( Sim_1 \) the reference plane (axis) from which the tilt angle \( \alpha \) will be estimated is provided from the sensor plane (\( x \) sensing axis).

According to Figure 2, the magnetic field provided by the magnets nicely couple with the ferromagnetic ribbon core of the flux-gate; the \( B_{NORM} \) relative to \( Sim_1 \) is show in Figure 3.

As a result, as shown in Figure 4, a new simple arrangement has been analyzed (\( Sim_2 \)). It performs the tilt-to-field conversion exploiting two rectangular magnets: one coupled to the tilting plane (the measurand) and the other static and fixed on a plane parallel to the PCB flux-gate sensor plane. To spread the field distribution generate by the magnets and partially shield from the external undesired noise-fields, two iron pole expansions have been added.
The $B_{\text{Norm}}$ values calculated from $S_{\text{Sim2}}$ are shown in Figure 5. As expected, this simpler topology provided lower $B_{\text{Norm}}$.

![Field distribution relative to $S_{\text{Sim2}}$. $d_1$ and $d_2$ heights are the zero-tilt distances of the upper pole-expansion and fulcrum to the lower pole-expansion respectively.](image)

**Fig. 5.** Simulated $B_{\text{Norm}}$ as a function of the tilt angle $\alpha$ calculated for the arrangement shown in Figure 4. The results have been obtained considering $B_r = 1$ T for each magnet, 80.0 mm length (diameter) and 5.0 mm thickness for the iron pole expansions, $d_1 = 25.0$ mm, $d_2 = 50.0$ mm, Vitrovac®6025 (Vacuumschmelze Hanau, Germany) sensing core and, neglecting the contribution due to the excitation and sensing coils.

The sigma-shaped sensitivity may probably be due to the mismatch between the upper pole expansion symmetry centre and the rotation fulcrum. Nonetheless, the calibration curve appears highly monotonic. Sensitivity of the tilt measurement system can be adjusted by changing the $S_{\text{FMS}}$ sensitivity, thus theoretically allowing the overall mean sensitivities reported in Table I.

Since the high monotonicity of the theoretical calibration curve, good theoretical sensitivity (Table I) and expected low cost and complexity implementation, this topology has been experimentally investigated and a prototype measuring system has been realized.

![Theoretical mean sensitivities of the TMS ($S_{\text{theo}}$) achievable with the arrangement shown in Figure 4.](image)

**TABLE I**

<table>
<thead>
<tr>
<th>$S_{\text{FMS}}$ [mV/µT]</th>
<th>$S_{\text{TMS-theo}}$ [°/mV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>104.9 (1)</td>
<td>31.5</td>
</tr>
<tr>
<td>52.4 (2)</td>
<td>15.7</td>
</tr>
<tr>
<td>26.4 (3)</td>
<td>8</td>
</tr>
<tr>
<td>13.3 (4)</td>
<td>4</td>
</tr>
</tbody>
</table>

A picture of the overall prototype system is shown in Figure 6. Most of the experimental setup has been realized exploiting no-ferromagnetic materials (aluminium, plastic, brass and wood). Notice as no shielding barriers have been added with respect to the simulated topology.

### III. Tilt Measurement System Performances

The previously selected arrangement exploits two magnets and pole expansions, thus allowing different system implementations depending on the actual magnets strength and size, and expansions shape and size.

Preliminary analysis have been performed exploiting three pair of magnets (Table II), 80.0 mm diameter and 5.0 mm thickness for the disc shaped iron pole expansions and 25.0 mm and 30.0 mm for distances $d_1$ and $d_2$ respectively (Figure 4).

![Exploited magnets. All the magnets (cost from 0.20€ to 1.40€ each) are produced by Supermagnete [8]. The three numbers composing the model code are the nominal length, width and height expressed in millimetres.](image)

**TABLE II**

<table>
<thead>
<tr>
<th>Name</th>
<th>Model</th>
<th>Nominal $B_r$ [T]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Q-19-13-06-N</td>
<td>1.26 ± 1.29</td>
</tr>
<tr>
<td>B</td>
<td>Q-20-10-05-N</td>
<td>1.29 ± 1.32</td>
</tr>
<tr>
<td>C</td>
<td>Q-20-20-03-N</td>
<td>1.32 ± 1.37</td>
</tr>
</tbody>
</table>

The data reported in this section are relative to a single-voltage-reading analysis of the FMS output-voltage as a function of the tilt angle $\alpha$. The FMS sensitivity has been chosen as a trade-off between the achievable TMS dynamic range and sensitivity ($S_{\text{FMS-theo}}$, 26.4 mV/µT).

The TMS sensitivity ($S$) has been first analysed in terms of least-squares interpolating line:

$$V_{\text{out}} = S \cdot (\alpha - \alpha_0) = S \cdot \Delta \alpha ,$$

where $\alpha_0$ is the tilt angle that provides a zero-output voltage from the FMS. Later, the INL has been calculated as:

$$\text{INL} = \sqrt{\frac{\sum_{i=1}^{M} r_i^2}{(M-1) \cdot V_{\text{out-max}}^2}} ,$$

where $r_i$ is the $i$-th residual from the interpoling line, $M$ and $V_{\text{out-max}}$ are the number of measurements and the maximum FMS output-voltage respectively.

The reference value of $\alpha$ has been estimated by using the optical setup depicted in Figure 7. Changes in its value have been obtained by a translation stage and an aluminium arm.
The laser diode was fixed to the experimental setup and the impinging angle $\beta$ was estimated. Hence, the height $h$ of the collimated laser beam projection ($\approx 2$ mm waist) onto the reference plane provided an estimation of $\alpha$:

$$\alpha = \arctan \left( \frac{h}{l} \right) - \beta. \quad (6)$$

Once estimated the $h = h_0$ height relative to the $\alpha_0$ angle, and neglecting that the system fulcrum did not exactly lie in the plane of refraction relative to the exploited mirror, the uncertainty associated with the $\Delta \alpha$ estimation is practically due to the uncertainty associated with the estimations of (i) $\Delta h = h - h_0$ and (ii) $l$. Thus applying the analytical procedure suggested by the International Standardization Organization (ISO) [9], the standard uncertainty associated to the $\Delta \alpha$ estimation was roughly estimated in $0.03^\circ$.

On the other hand, the FMS output voltage ($V_{out}$) was measured by a single direct reading of a 6 1/2 Digit Multimeter (34401A, Agilent, USA).

### A. Measurement procedure and obtained data

Exploiting the experimental setup previously shown in Figures 6 and 7, the upper plate was moved using the translation stage in order to obtain $V_{out} \approx 0$ V, thus defining $h_0$. Then, moving the translation stage in order to induce an $\alpha$ variation of about $0.1^\circ$ per step, double-round-trip measurements have been acquired for each magnet. For each $\alpha$ variation step, a single reading of both $V_{out}$ and $\Delta h$ have been recorded, thus providing an estimation of $\Delta \alpha$. The extent of the inspected $\Delta \alpha$ ranges have been determined by the output voltage $V_{out}$ saturation or by the limited translation stage range.

The obtained results are shown in Figure 8 and Table III. As expected, not only $B_r$, but also shape and size of the exploited magnets concur to the overall system performances. Notice as the experimental results reported in Table III and Figure 8 are consistent with the simulative analysis previously reported in Figure 3.
TABLE III
TILT MEASUREMENT SYSTEM SENSITIVITY AND INTEGRAL NON-LINEARITY MEASURED FOR THE THREE MAGNETS CONSIDERED.

<table>
<thead>
<tr>
<th>Magnets</th>
<th>S [V/°]</th>
<th>INL %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.1027</td>
<td>1.66</td>
</tr>
<tr>
<td>B</td>
<td>1.2972</td>
<td>3.14</td>
</tr>
<tr>
<td>C</td>
<td>2.3491</td>
<td>0.97</td>
</tr>
</tbody>
</table>

IV. DISCUSSION AND CONCLUSIONS

Two-axis inclination measurement system can be implemented using a planar flux-gate sensor. The resulting contactless device takes advantage from different flux-gate sensor characteristics such as low temperature coefficient, low-cost, high sensitivity and linearity, thus providing an overall system sensitivity $S$ up to 2.3491 V/°and INL down to ≈1%. Moreover, the measuring device is subject neither to mechanical wearing nor stress, thus leading to higher reliability.

In addition, the good agreement between the simulation and the experimental results suggests the possibility of expanding the dynamic range with no excessive efforts and drawbacks.

Moreover, the TMS size could be reduced thanks to the flexible circuit technology or Si flux-gate [7], thus probably leading to further cost reduction.

Furthermore, absolute tilt measurement may simply be achieved overturning the $Sin 3$ topology and coupling the measurement plate to a pendulum. However, in such a case the accuracy of the TMS will be highly affected by the stick-slip effects of the pendulum bearings.

Even though flux-gate sensors are known to provide low temperature coefficient (less than 30 ppm/°C), magnetic system performance are known to be highly affected by temperature variations even below the Curie temperature. Nevertheless, the dimensions of the measurement setup (about 3 m, Figure 7) will require a huge thermostatic chamber, thus temperature dependence of the TMS performance has not been investigated.

ACKNOWLEDGMENT

The authors wish to thank Lorenzo Argenidi for his contribution during the experimental activities.

Research partially supported by grant “Signal processing and characterization techniques for a novel Si-based-Fluxgate sensor” 2005091051 from MIUR, Italy.

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