Low-Voltage Fluxgate Magnetic Current Sensor Interface Circuit with Digital Output for Portable Applications

M. Ferri∗, A. Surano∗, A. Rossini∗, P. Malcovati∗, E. Dallago∗, A. Baschirotto†

∗Department of Electrical Engineering, University of Pavia, Italy
{massimo.ferri, antonio.surano, andrea.rossini, piero.malcovati, enrico.dallago}@unipv.it
†Department of Physics, University of Milano Bicocca, Italy
andrea.baschirotto@unimib.it

Abstract—In this paper we present a complete low-voltage, low-power and high linearity CMOS interface circuit for fluxgate magnetic sensors for current measurement applications. The integrated circuit provides the correct excitation signal to the fluxgate sensors and reads-out the sensor signals from the sensing coils. The proposed circuit allows us to deal with sensors featuring different values of the excitation coil resistance and to process the sensing coil signals with a power consumption lower than 1 mW. The interface circuit consists of three different modules, namely a timing block, an excitation block and a read-out chain. The interface circuit, which has been implemented with two different excitation circuits, operating at 5 V and 3.3 V, respectively, without any high-voltage stage, has a synchronous demodulation of the even harmonics, in order to extract the value of the external magnetic field. Furthermore, it is possible to switch-on a 13 bit ADC, to provide at the output the demodulated signal as a digital word.

I. INTRODUCTION

Magnetic sensors represent an essential block in several industrial and research applications, such as environmental monitoring [1], current measurements [2]–[4], electronic compasses [5]–[7] and proximity detection systems [8]. Fluxgate sensors are typically used to measure low values of magnetic field, such as the Earth magnetic field [5] or the magnetic field induced by low currents. When fluxgate magnetic sensors are used for current measurements, the electronic interface circuit plays an important role, since it must guarantee high linearity, low-power consumption (for portable applications), reliable results and high magnetic noise rejection. In this paper we present a complete low-voltage and low-power CMOS interface circuit for fluxgate sensors. The proposed circuit allows us to excite sensors with different values of the excitation coil resistance and to process the sensor signals. The chip consists of three different modules, namely a timing block, an excitation block and a read-out chain. The interface circuit, whose block diagram is shown in Fig. 1, has been implemented with two different excitation circuits, operating at 5 V and 3.3 V, respectively, without any high-voltage stage [9]. The read-out circuit allows us to retrieve the information on the external magnetic field from the sensing coil signal. In the interface circuit, we included also a 13 bit ADC [10], to provide the measured magnetic field value as a digital word. The timing block provides control signals for both excitation and sensing. In the considered current measurement application, we have used a fluxgate sensor with an excitation coil featuring 140 Ω resistance and 4 µH inductance, which needs to be excited with a 16 mA current signal with odd symmetry at 100 kHz [11].

II. 3.3-V EXCITATION CIRCUIT

Fig. 2 shows the excitation circuit operating at 3.3 V. It consists of an H-Bridge, which exploits an external inductance to generate a triangular current excitation signal starting from a square-wave voltage signal. In order to achieve the desired excitation signal, the value of the external inductance is 380 µH. The external 3.3-V, 400-kHz clock, after frequency division by 4, drives the H-Bridge with two opposite square waves at 100 kHz. Fig. 3 shows the excitation signal obtained.

III. 5-V EXCITATION CIRCUIT

Fig. 4 shows the excitation circuit with 5-V power supply. It consists of a triangular wave generator, a voltage driven current generator, a current mirror, and a H-Bridge. The triangular wave generator provides a 130-mV signal around 2.5 V, obtained by integrating the frequency-divided clock and level-shifting it around the proper average value. It is possible to modulate the amplitude of the signal changing the value
The Wilson current mirror amplifies the current by $K = 10$, thus leading to a 20-mA peak current signal. The 200-kHz H-Bridge driving signals are used to switch alternatively the direction of the current flowing into the excitation coil of the sensor. In particular, when signal $S_1$ is high and signal $S_2$ is low, transistors $M_3$ and $M_7$ are switched-on, while transistors $M_6$ and $M_5$ are switched-off. During this period, the current flowing through the sensor is $K I_{ref}$. By contrast, when signal $S_1$ is low and signal $S_2$ is high, transistors $M_6$ and $M_5$ are switched-on, and the excitation current flowing through the sensor is $-K I_{ref}$. As a result, the sensor is excited with a 40-mA peak-to-peak current, as required. Without the H-Bridge, this behavior would have been possible only with a symmetric supply voltage ($\pm 5$ V).

IV. Read-out Chain

Fig. 5 shows the block diagram of the read-out chain. In the presence of an external continuous magnetic field, the even harmonics of the signal obtained from the sensing coils of the sensor are not zero. In particular, the spectral component carrying most of the information is the second harmonic of the excitation signal. Therefore, the read-out chain performs a synchronous demodulation of the even harmonics, in order to extract the value of the external magnetic field component.

A. First Gain Stage

The first gain stage of the read-out chain is an instrumentation amplifier, which amplifies by 35 dB the differential signal obtained from the sensing coils of the fluxgate sensor. An instrumentation amplifier is required to eliminate common-mode coupling signals. Fig. 6 shows the schematic of the instrumentation amplifier. Each operational amplifier used in this circuit consumes 168 $\mu$W, with a supply voltage of 3.3 V, achieving a bandwidth of 133 MHz with a phase margin of 76$^\circ$.

B. Coherent Orthogonal Demodulator

Since the information on the external magnetic field in the fluxgate sensor output signal is contained in the even harmonics of the excitation signal, it is necessary to down-convert this information to the base-band. The demodulation is performed by multiplying the sensing signal with a 200-kHz square-wave. In order to avoid degradation of the down-conversion process in the presence of unwanted phase shifts...
between the sensor signal and the 200-kHz square-wave, we used a quadrature demodulator. In particular, the sensing signal is multiplied by a couple of orthogonal square-waves. Ideally, at the output of the quadrature demodulator, the signal should be reconstructed using

\[ V_{\text{out}} = V_{\text{out},0^\circ} + V_{\text{out},90^\circ} \]

where \( V_{\text{out},0^\circ} \) and \( V_{\text{out},90^\circ} \) are the output signals of the two quadrature paths. To simplify the circuit, the reconstruction has been implemented simply by adding \( V_{\text{out},0^\circ} \) and \( V_{\text{out},90^\circ} \), according to

\[ V_{\text{out}} = V_{\text{out},0^\circ} + V_{\text{out},90^\circ} \]  \hspace{1cm} (2)

The error between the two algorithms depends on the value of the phase displacement, as shown in Fig. 7. If the phase displacement is constant, as it is in the fluxgate sensor, this leads to a gain error, that can be compensated.

C. Sallen-Key Filter

The output of the demodulator contains the useful information at \( dc \), but it also contains several spurs. Therefore, we introduced a filter for removing any high-frequency unwanted signal components. The filter implements a second order Butterworth transfer function with a cut-off frequency of 550 Hz and a \( Q \) factor of 0.707, to guarantee a maximally flat response in the base-band. Fig. 8 shows the schematic of the circuit.

D. Programmable Gain Amplifier

The Sallen-Key filter is followed by a final gain stage, which amplifies the \( dc \) signal proportional to the magnetic field, obtained at the output of the filter, with a programmable gain. Setting the value of digital signals \( b_0 \), \( b_1 \) and \( b_2 \), it is possible to program the gain of the stage, according to Tab. I.

E. Incremental ADC

The schematic of the 13-bit A/D converter [10] is shown in Fig. 9. The A/D converter, based on the switched-capacitor (SC) technique, consists of a fully-differential resettable integrator and a comparator, whose output is connected to a 13-bit counter. The ADC can be enabled or disabled, according to the desired power consumption. The allowed input signal range is variable, with a maximum of about 1 V.

V. EXPERIMENTAL RESULTS

The proposed interface circuit has been integrated in a 0.35-\( \mu \)m CMOS process. Fig. 10 shows the micro-photograph of the chip. Fig. 11 shows the maximum linearity error of the system (fluxgate sensor and interface circuit) normalized to
the full-scale of the applied magnetic field as a function of the full-scale magnetic field itself. In order to obtain this curve, we applied the magnetic field with a couple of Helmholtz coils. The axis of the Helmholtz coil has been oriented perpendicular to the Earth magnetic field, to avoid undesired contributions to the applied magnetic field. The maximum linearity error degrades for large values of the full-scale magnetic field, because of the saturation in the ferromagnetic material of the considered fluxgate sensor, as expected. Fig. 12 shows the transfer characteristic of the system for a full-scale magnetic field of 100 µT (±50 µT). Finally, Fig. 13 shows the relative linearity error with the same full-scale magnetic field.

REFERENCES


