

Fully digital fluxgate magnetometer – first results

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Abstract - Presented paper describes design, implementation and first results of the fully digital fluxgate magnetometer. The magnetometer operates in feedback configuration and uses fully digital signal detection realized in the digital signal processor (DSP). The magnetometer has measuring range $\pm 100 \mu\text{T}$, the linearity error is less than 40 ppm of FSR, noise $1.08 \text{ nT}_{\text{RMS}}/\sqrt{\text{Hz}}@1\text{Hz}$ and the frequency range of measured magnetic field is 15 Hz.

I. Introduction

The fluxgate magnetometers are usually used for high precise detection of weak magnetic fields. The typical applications are military and space magnetometers [1], medical applications [2], geological and archaeological prospecting and much more. Up to now the absolute most of the constructed fluxgate magnetometers are analog. In last several years we can observe an attempt of the digitisation of the magnetometers led by necessity of integration of the magnetometers to the automatic measurement and DAQ systems, computer based data post-processing and data visualisation.

Up to now three streams of the fluxgate magnetometers digitisation are known:

- Analog magnetometer with consequential digitisation,
- Application of delta-sigma modulation to the sensor feedback loop,
- Fully digital detection of the fluxgate sensor output signal.

The first principle is mostly used for realisation of the fluxgate magnetometers with digital output. In the laboratory conditions the analog outputs of the magnetometer are mostly digitised using precise voltmeters and data are collected using GP-IB, RS-232 or other standard bus. In case of analog magnetometers with direct digital output, the analog signals are digitised by use of high-resolution analog-to-digital converters, usually based on delta-sigma modulation.

The second principle, application of the delta-sigma modulation, is based on adding of the Δ - Σ modulator to the sensor feedback loop. The output signal of the magnetometer is then modulated bit-stream, which has to be digitally post-processed. Although the endeavour of the application of this principle for satellite use was recently published [3], the problems with stability of the feedback system [4] and absence of any advantage compared to the placement of the modulator outside the feedback loop (analog magnetometer with consequential digitisation) [4], excluding possible increment of the modulation order published in [5], eliminate this principle from broad applications.

Compared to the previous two principles, there are several reasons for the application of the fully digital signal detection in the design of fluxgate magnetometers. The first and also the most important reason is a possibility of change of the magnetometer parameters without necessity of re-soldering of analog circuits. As an example of this feature we can mention magnetometers for satellite missions. During these missions the satellite flies through areas with different changes of the measured fields. In areas with fast change of magnetic field (near magnetic field of the Earth) the magnetometer is switched into the mode with fast time-response. But this fast-mode usually decreases the magnetometer resolution. During the fly in areas with slow change of the magnetic field (interplanetary magnetic field) the magnetometer is switched to the slow mode with higher resolution. Other reason is possible more sophisticated signal detection and possible signal post-processing. Temperature dependence of the digital magnetometer can be also lower compared to the analog magnetometer with separated digitizer, because the number of temperature-dependent analog circuits is reduced.

The idea of digital signal detection of the fluxgates is not new. The first digital fluxgate magnetometer was reported by Auster et al. in 1995 [6]. Up to now probably the best fully digital fluxgate magnetometer was the magnetometer for the Astrid-2 satellite designed and realized by Pedersen et al. [7]. But current offer of faster and still more precise A/D and D/A converters together with broad range of digital signal processing offer new possibilities for the design.

II. Fully digital fluxgate magnetometer realization

A. Hardware

The sensor is excited by current generated by excitation unit using tuning technique similar to the standard analog magnetometers. Sensor output signal is also tuned [8] and then it is pre-amplified by front-end amplifier. Front-end amplifier also includes 2nd-order anti-aliasing filter preventing leakage of higher frequencies to the base-band of the digitized data. High-speed A/D converter AD7664 with nominal resolution of 16 bits converts pre-amplified signal and passes data to the 16-bit fixed-point digital signal processor ADSP2181. DSP handles detection of the signal proportional to the measured magnetic field, which is modulated on even-harmonics of the excitation signal. Detected signal is reconstructed to the feedback signal by use of low-speed precise D/A converter DAC1220 and it is also sent from the DSP to PC as output data of the magnetometer using RS-232 link. The 8-bit host processor AT89C2051 is added between the DSP and DAC and it is appointed for communication with PC. This solution saves the DSP calculation power, because DSP does not include hardware UART. Time delay caused by the double sending of the data from DSP to host processor and from host processor to DAC is negligible compared to the long time constant of the feedback system. Reconstructed analog signal from the DAC is converted into the feedback current and then it is used as a feedback signal to the sensor.

Our hardware solution of the fully digital fluxgate magnetometer has two main advantages. The first of them is the direct derivation of the excitation control signal from sampling control signal, which is generated by DSP, using programmable frequency divider. It means that in terms of programme we can set the sampling frequency of the ADC in range from 8 ksp/s up to 480 ksp/s when integer number of samples per period of detected signal and constant excitation frequency are guaranteed. It prevents the leakage of the spectrum of detected signal.

The second goal is that our magnetometer behaves as the Analog Devices evaluation kit EZ-KIT. It means that after starting up the magnetometer, the DSP downloads program from external boot memory and starts it. This program simulates behaviour of mentioned EZ-KIT and thus the magnetometer can directly co-operate with the evaluation tools and programs supplied by Analog Devices. This solution very effectively saves evaluation time.

The main weak point of the fully digital magnetometer implementation is the DAC non-linearity [7]. Only 1-bit DAC converters have linearity error small enough to be used in the fully digital magnetometer. According to this fact, the two DAC converters were tested for the application in our magnetometer. The first of them was commercially available 20-bit DAC1220 based on the Δ - Σ modulation principle made by Burr-Brown. The converter was placed on the PCB of the magnetometer during the testing. The second one was DAC based on PWM principle [9]. This converter was realised on the separate PCB. The modulator has been implemented in the CPLD and it has serial interface fully compatible with synchronous serial port of the DSP. Nominal resolution of the modulator is 18 bits. The modulator is followed by 1-bit DAC and cascade of four 2nd-order analog low-pass filters. Although the PWM based DAC proved slightly lower noise, the DAC1220 was used in the final magnetometer implementation because of its smaller non-linearity, which is in range from 0 to -6 ppm of FSR compared to the non-linearity from -20 to $+20$ ppm of FSR of the PWM DAC.

More details about hardware implementation can be found in [10].

B. Digital signal detection

Most of the analog fluxgate magnetometers use second-harmonic detection of the modulated signal from fluxgate sensor, when the phase-sensitive demodulator is used for the detection [11]. In the realization of our digital fluxgate magnetometer we have implemented the phase-sensitive demodulator in the digital domain. The reference sine-wave signal is stored in the internal program memory of the processor. Each sample is multiplied with relevant point of the reference signal. The result of multiplication is then filtered using low-pass digital filter. A moving average filter, which represents in fact FIR filter with unity coefficients, was used in our implementation. Because the sensor excitation signal is derived from the sampling signal, the phase-shift between sensor output signal and excitation signal is constant and it is digitally compensated.

The digital detector can be mathematically described as product of input signal with reference signal

$$v_M(n) = v_I(n) \cdot v_R(n) = V_I \sin\left(\frac{2\pi n}{N} + \varphi_I\right) \cdot V_R \sin\left(\frac{2\pi n}{N} + \varphi_R\right) =$$

$$= \frac{1}{2} V_I V_R \left[\cos(\varphi_I - \varphi_R) - \cos\left(\frac{4\pi n}{N} + \varphi_I + \varphi_R\right) \right] \quad (1)$$

where $v_I(n)$ is an input signal and $v_R(n)$ is a reference signal, both are harmonic and represented in the digital-domain. The mean value after filtering using moving average filter of this multiplication is

$$\begin{aligned} v_{\text{PSD}}(n) &= \frac{1}{N} \sum_{i=n-N+1}^n v_M(i) = \frac{1}{N} \sum_{i=n-N+1}^n v_I(i) v_R(i) = \\ &= \frac{V_I V_R}{2N} \left[\sum_{i=n-N+1}^n \cos(\varphi_I - \varphi_R) - \sum_{i=n-N+1}^n \cos\left(\frac{4\pi i}{N} + \varphi_I + \varphi_R\right) \right] \end{aligned} \quad (2)$$

Because the mean value of the harmonic signal is zero (right sum of cosines) and phase-shift between input and reference signals is compensated, the amplitude of input (detected) signal can be then calculated as

$$V_I = \frac{2}{N V_R} \sum_{i=n-N+1}^n v_I(i) v_R(i) \quad (3)$$

The digital PSD is followed by digital integrator, which is used for getting of sufficient feedback loop gain in the magnetometer baseband.

B. First results

The magnetometer measuring range was set to $\pm 100 \mu\text{T}$, which is usually used for measuring the Earth magnetic field and detection of its anomalies. The best results were gained for sampling frequency of 16 kHz, when the linearity error was in the range of ± 40 ppm of FSR corresponding to ± 4 nT (see Figure 1). Up to 64 ksp/s the linearity error was within the range of ± 60 ppm of FSR. Then the linearity error starts to rapidly increase and for sampling frequencies more than 140 kHz the magnetometer becomes unstable. The noise of the magnetometer is $1.08 \text{ nT}_{\text{RMS}}/\sqrt{\text{Hz}}@1\text{Hz}$, which corresponds to $2.64 \text{ nT}_{\text{RMS}}$ in the frequency range from 0.1 Hz to 10 Hz (see Figure 2). The effective resolution of the magnetometer is 16 bits. Frequency range of measured magnetic field is 15 Hz and it is limited by the digital integrator.

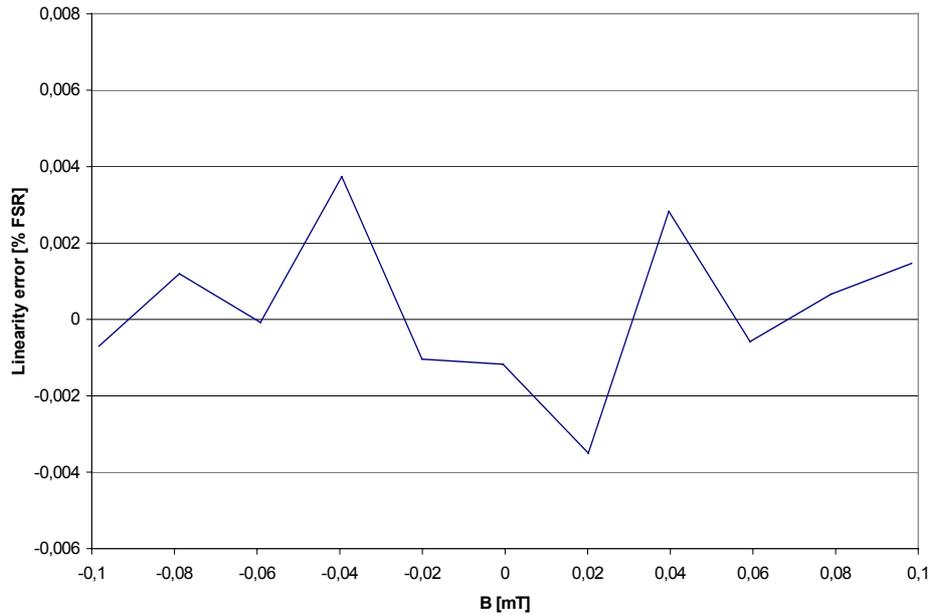


Figure 1. Linearity error

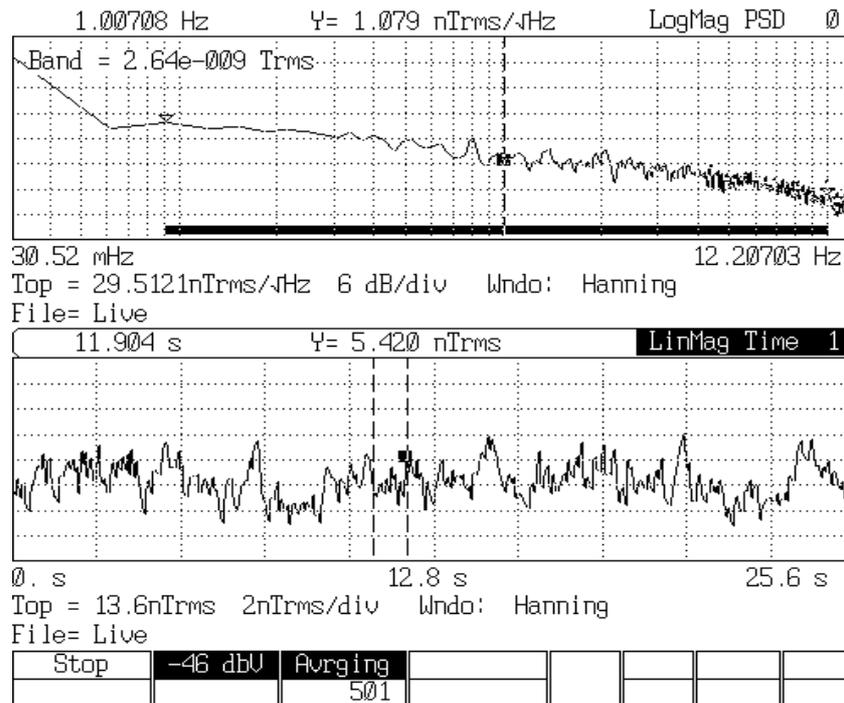


Figure 2. Noise of the magnetometer

III. Conclusions

The implementation of fully digital fluxgate magnetometer together with first results was presented on this paper. The gained parameters of the magnetometer are still not comparable with precise analog fluxgate magnetometers. But these parameters were gained during the first implementation and tests and thus they are preliminary results. Namely the algorithm of the digital detection is still under construction. Use of optimum reference waveform and deceasing of the noise of analog front-end amplifier will further improve the instrument parameters.

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