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Excess Loop Delay compensated Electro-Mechanical Bandpass Sigma-Delta Modulator for Gyroscopes

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Abstract

This paper presents a new excess loop delay (ELD) compensated micro-electro-mechanical sigma-delta modulator (ΣΔM) incorporating a gyroscope in series with a second-order electrical bandpass filter. The bandpass filter is optimized for large ELDs and is realized in a feedforward structure. The ΣΔM is implemented on a field programmable gate array (FPGA) emulating continuous-time (CT) behavior in order to investigate the ELD effect. The digital setup gives also maximum flexibility in testing and characterization of different structures in a fast and efficient way. Measurements show stable modulators, with ELDs of nearly one time period of the sampled system, achieving in-band noise (IBN) below -60 dBFS. This paper demonstrates that the stability of ΣΔ modulators with large ELDs can be ensured with the new ELD compensation technique.

Keywords: Excess Loop Delay; Sigma-Delta Modulator; Closed-loop; Bandpass; Gyroscopes

1. Introduction

In the automotive industry, micromachined angular rate sensors are used for several applications like rollover detection, inertial navigation, and electronic stability program. Inertial sensors have been sensed in an open loop scheme[1], but future markets will demand higher performance in terms of resolution and insensitivity against temperature and process variations. Temperature has a large influence on the sensor quality factors and therefore on the dynamics of the sense element. Process variations are responsible for imperfection in the mechanical structures resulting in an error component, the so called quadrature signal, which can easily exceed the actual signal. The primary oscillation of a gyroscope can be controlled by a drive loop consisting of a phase looked loop (PLL) and an automatic gain control (AGC). In the secondary mode all these problems are solved by using a read out interface in a closed-loop fashion. Due to the force-feedback, parameter variations of the sensor are suppressed and as the sensors mass is regulated to its idle position, the linearity can be improved as well. A further advantage of applying force-feedback is the increase of the dynamic range. In order to improve the resolution, a readout interface based on ΣΔ modulation is implemented, which produces an intrinsically digital output. Beside all the improvements mentioned above due to the force-feedback, two further effects namely the noise shaping effect as well as the

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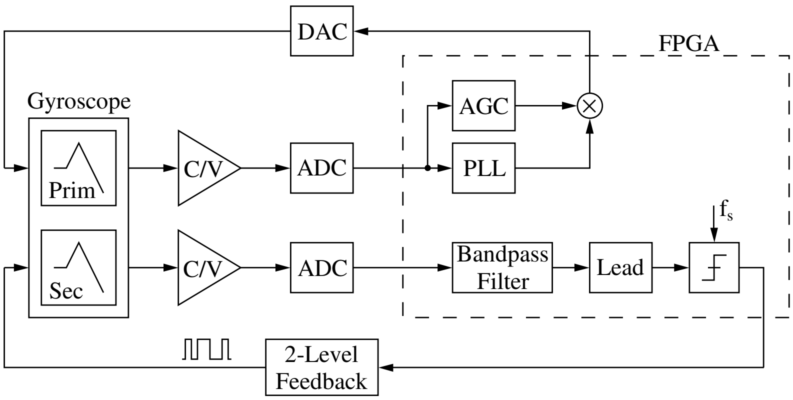

Fig. 1: System-level overview consisting of the drive-loop based on a PLL and AGC and a continuous-time ΣΔ sense-loop with bandpass loop filter and single-bit quantizer implemented on an FPGA.

oversampling can be used. For many years only the sensing element has been used as a low-pass noise shaping filter[2]. Recent works report on the use of additional electronic low-pass filters to further improve the noise shaping behavior[3,4]. Since the output characteristic of a gyroscope is a narrow-band amplitude modulated signal at the drive frequency a bandpass noise shaping filter is beneficial[5]. A fourth-order bandpass ΣΔM is reported[6] realized in switched-capacitor (SC) techniques. Compared to SC, CT implementation is not affected by noise folding and has therefore an intrinsic lower noise floor. Hence, a higher signal-to-noise ratio or as a tradeoff, less power consumption can be achieved, which is the motivation for this work. In CT implementation a non-ideality, namely excess loop delay, arises, which degrades the performance or even results in an unstable loop. This work shows that large ELD can be compensated and therefore prevents the modulator from instability[7,8].

2. System-level

Fig. 1 shows a system-level representation of a gyroscope using separate sense and feedback electrodes for both, the primary and secondary structures allowing front-ends without time-multiplexing. Also shown are the corresponding control loops implemented on an FPGA. With this methodology, a maximum flexibility is given to prove and characterize different readout concepts[9]. The angular rate sensor consists of two coupled mass spring resonators. Since the Coriolis Force is $\boldsymbol{F}_c = -2\ m\ \boldsymbol{\Omega} \times \boldsymbol{v}_p$, where m is the mass and $\boldsymbol{\Omega}$ is the angular rate, a closed drive loop is essential for keeping the primary velocity $\boldsymbol{v}_p$ constant. The primary mass is excited to its resonance frequency with constant amplitude employing a PLL and AGC, which are implemented digitally on the FPGA. For actuation a digital-to-analog converter (DAC) is used applying a sine-wave. The secondary mass is used to detect the angular rate. The Coriolis Force due to an external rotation will excite the secondary resonator orthogonal to the movement of the primary oscillator. The differential capacitance change caused by the deflection is detected by a CT capacitive-to-voltage (C/V) converter implemented as a charge integrator. Its output is converted into the digital domain using an analog-to-digital converter (ADC). The second-order CT bandpass filter and the lead compensator are implemented on the FPGA emulating CT behavior and guaranteeing highest flexibility. Beside the filter, a non-return-to-zero single-bit quantizer is implemented, which is sampled with f_s=8×f_d, where f_d is the drive resonance frequency. A single-bit quantizer is used due to its inherent linearity compared to multi-bit quantizers. The digital output signal of the ΣΔM is used to generate electrostatic force feedback by applying two defined voltages to separate feedback electrodes compensating approximately the deflection of the proof mass.

3. Electro-Mechanical ΣΔM

For the ΣΔM a feedforward architecture is advantageous, if the sensing element is included in the loop. Compared to distributed feedback architectures, sensor variations do not have an impact on the position of the zeros of the loop filter[4]. As there is no access to the velocity node of the gyroscope a lead compensator is needed to guarantee loop stability. This lead compensator replaces the missing feedforward signal path. The noise-shaping

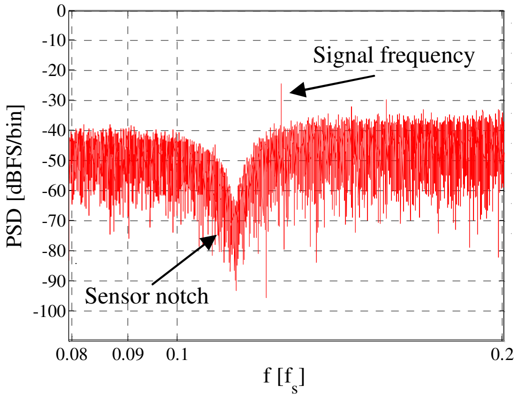

Fig. 2: Measured spectrum of the second-order ΣΔM sampled with $8\times f_d$. The notch is defined only by the sensor transfer characteristic.

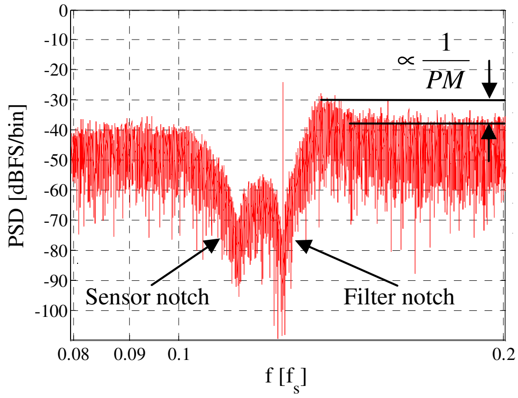

Fig. 3: Measured spectrum of the fourth-order ΣΔM sampled with $8\times f_d$. The additional notch due to the electrical bandpass filter improves the performance, since noise is pushed out of the signal band.

filter is implemented as a bandpass rather than a low-pass filter. Compared to low-pass ΣΔM, bandpass solutions can use much lower sampling frequencies relaxing the circuit requirements in terms of power consumption[5,10]. Bandpass ΣΔM realized in CT are preferable for low power solutions of gyroscope readout circuits. The entire filter is designed with a MATLAB™ Toolbox for the Discrete Time Simulation of Continuous Time Sigma-Delta Modulators (DISCO). The modulator is designed in discrete-time and afterwards converted into continuous-time. Non-idealities such as ELD which arise in continuous-time modulators can be regarded. Within the DISCO Toolbox an automatic ELD compensation is done. The fundamental idea behind that is to make the impulse response of the filter with ELD equal to one without. Therefore a CT filter-template with the required degrees of freedom and ELD is designed. To achieve the ELD compensated filter the degrees of freedom of the filter-template are optimized with respect to an equal impulse response of an ELD free filter. Using an ELD compensated loop filter, the ΣΔM achieves the same performance compared to a ΣΔM without ELD - even in case of large delays, which would drive the uncompensated filter into instability.

4. Experimental Results

Fig. 2 shows the spectrum of the output bitstream of a second-order ΣΔM with the noise shaping effect originated only by the sensor transfer characteristic. Optimum performance is achieved when both primary and secondary resonance frequencies are identical, obtaining matched-mode condition[6]. Due to the mechanical properties the sensor's notch frequency is located below the Coriolis signal, which is located at f_d, allowing only split-mode. An additional electrical bandpass filter with center frequency f_d improves the performance significantly as shown in Fig. 3. The large ELD of $0.955\times T_s$ due to the delay of the ADC forces the modulator to instability if no ELD compensation is applied. With compensation a peak is visible which is directly proportional to the phase margin (PM) of the closed-loop system. This effect occurs due to realization limitations of the ELD compensated loop filter. The PM can be increased by reducing the sampling frequency to $6\times f_d$, but at the cost of a reduced oversampling ratio

Table 1. Measurement results of the in-band noise for different filter configurations over a bandwidth of 100Hz at the drive frequency f_d.

Topology	f_s	IBN
2^{nd}- order ΣΔM (Sensor only)	$8\times f_d$	-25.0 dBFS
4^{th}- order ΣΔM (Sensor & 2^{nd}- order filter)	$8\times f_d$	-60.1 dBFS
4^{th}- order ΣΔM (Sensor & 2^{nd}- order filter)	$6\times f_d$	-61.0 dBFS

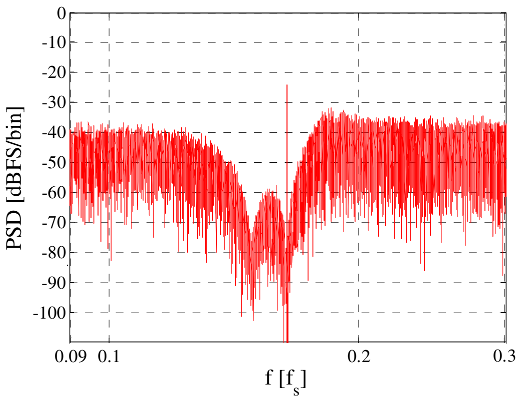

Fig. 4: Measured spectrum of the fourth-order ΣΔM sampled with $6 \times f_d$. A lower sampling frequency improves the stability of the closed-loop system.

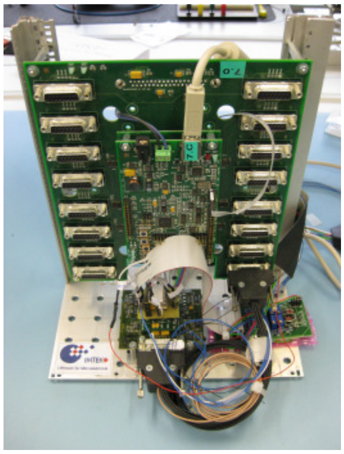

Fig. 5: Evaluation board with the gyroscope, CT front-end and FPGA comprising drive and sense control schemes.

as shown in Fig. 4. Table 1 summarizes the measurement results over a bandwidth of 100Hz, while Fig. 5 shows the laboratory setup.

5. Conclusion

This work presents a fourth-order electro-mechanical ΣΔM implemented on an FPGA emulating CT behavior. The bandpass filter is realized in a feedforward summation architecture in order to be insensitive to variations of the sensor element. A non-ideality, namely ELD, which arises in CT implementations, is compensated successfully with the automatic ELD compensation technique provided by the DISCO Toolbox resulting in stable closed loops. For proof of concept and for having a flexible test environment, the modulator is implemented on an FPGA.

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