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Implementation of a Modulated Lowpass ΔΣ-Modulator for MEMS Gyroscopes with Low-Power Consumption and Low Sampling

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Abstract

This paper reports on the implementation of a closed-loop readout concept for a vibratory MEMS gyroscope. The system is based on electro-mechanical (el.-mech.) ΔΣ-modulation and implemented on an integrated circuit (ASIC) with incorporation of a field programmable gate array (FPGA) for rapid prototyping. The sense loop exhibits two modulation stages for the detection of the Coriolis-signal and thus reduces the sampling frequency \( f_s \) by a factor of 4 and 100 compared to bandpass- and conventional lowpass modulators, respectively. This concept enables the design of low-power interfaces with very low \( f_s \), reducing the power consumption in the analog and digital domain. Measurements results of the readout circuit are presented using a MEMS gyroscope, which demonstrates the functionality and competitiveness of the concept.

Keywords: Delta-Sigma Modulator; Low-Power; MEMS; Gyroscope; Drive Loop; Lowpass; Bandpass; FPGA

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1. Introduction

Capacitive MEMS vibratory gyroscopes rely on the detection of the Coriolis-force and are frequently deployed in the automotive sector for the electronic ride stabilization of cars [1]. They are also used in portable devices e.g. smart-phones and tablets for gaming applications or indoor navigation [2]. These devices are mostly battery powered and for a long operational time, the readout electronic must offer low-power consumption.

For the detection of the Coriolis force a drive loop based on a phase locked loop (PLL) is deployed. The drive loop excites the drive mass at the resonance frequency and provides the sampling clock for the implemented closed-loop ΔΣ-modulator in the sense loop [3]. This means a feedback force is applied to the sense mass to compensate the Coriolis force which is acting on the gyroscope and as a result the sense mass remains at its idle position. The sense readout can also be implemented in an open-loop readout scheme [4-5], but the implementation of closed-loop el.-mech. ΔΣ-modulators is beneficial due to high linearity and inherent digital output signal. Additionally, nonlinearities are suppressed due to the application of a feedback force [6-9].

2. Closed-Loop Readout for MEMS Gyroscopes based on ΔΣ-Modulation

State of the art readout interfaces for MEMS gyroscopes require an enormous amount of digital circuitry for post-processing of the angular rate signal. In implementations for gyroscope readout the digital part can account for more than 20% of the total power consumption [5].

The complete power consumption of interfaces based on closed-loop ΔΣ-modulation is separated into the analog part and the digital part. The raw digital output signal of conventional ΔΣ-modulators is highly oversampled and requires digital circuitry for post-processing. To achieve high oversampling ratios (OSR) over the bandwidth \( f_b \), conventional bandpass or lowpass ΔΣ-modulators sample with at least 4 or 100-times faster than the mechanical resonance frequency of the drive resonator (\( f_{\text{drive}} \)) as given in (1).

\[
OSR = \frac{f_s}{2 \cdot f_b}
\]  

This means the sampling frequency \( f_s \) can reach several MHz [7]. As a result, the requirements for the subsequent digital circuitry, which is used for the post-processing of the output signal, are increased. To enable low power consumption it is beneficial to design ΔΣ-modulators with lower \( f_s \). By lowering \( f_s \), the dynamic power consumption of the digital part is reduced according to (2).

\[
P_{\text{diss}} \propto C_{\text{load}} \cdot V_{dd}^2 \cdot f_s
\]

Additionally, the power consumption in the analog domain is reduced, because the operational amplifiers which are deployed in the analog sense loop for noise shaping can be designed with a lower gain bandwidth product and slew rate [10].

3. Implementation of the Lowpass ΔΣ-Modulator Readout Circuit

3.1. Constraints of the OSR

In this work the resonance frequency \( f_{\text{drive}} \) (9.27kHz) of the drive resonator is used as sampling clock for the sense loop comparator and the bandwidth of the detectable angular rate signals is \( f_b = 40 \) Hz. This results in an OSR of 115. The OSR depends directly on the mechanical sensor resonance frequency and thus, if a higher OSR is desired a MEMS gyroscope with higher resonance frequency is necessary. This is possible since the sensor manufacturers tend to develop gyroscopes with higher mechanical frequencies of up to 100 kHz, due to the fact that
these sensors are less susceptible to ambient vibrations which occur at low frequencies [11]. To demonstrate the functionality of the readout concept, the implemented OSR in this work is large enough.

3.2. Description of the Readout System

The drive loop shown in Fig. 1 excites the drive mass with constant \( f_{\text{drive}} \) and amplitude, using a PLL and an amplitude gain control (AGC). The sense loop relies on the modulation stages \( m_1 \) and \( m_2 \) as shown in Fig. 1. Due to the fact that the modulated sensor behaves like a 1st-order lowpass-filter in the band of interest, it is possible to use a lowpass-filter for noise shaping [10]. The first modulation stage \( m_1 \) modulates the Coriolis-signal to the base-band with the frequency \( f_{\text{mod}} = f_{\text{drive}} \). The phase of the \( f_{\text{mod}} \) for \( m_1 \) is adjusted to the Coriolis signal. Thereby the Coriolis-force is compensated by the sense loop. The signal is filtered with a 2nd-order lowpass-filter and digitized by a comparator which is clocked with \( f_s \). The second modulation stages \( m_2 \) modulates the signal back to \( f_{\text{drive}} \) for the application of the feedback voltages. The HV-feedback stage converts the modulated low voltage feedback signal into high voltages and applies it to the MEMS gyroscope. Therefore, a 3rd-order modulated el-mech. lowpass \( \Delta \Sigma \)-modulator is implemented.

The front and back-end of the readout ASIC together with a FPGA and MEMS gyroscope are combined for the implementation. This hybrid implementation architecture allows rapid prototyping of different designs.

Fig. 1. System level diagram of the readout circuit. The readout circuit is implemented in a hybrid environment. The modulated sensor behaves like a 1st-order lowpass-filter in the band of interest, thus it is possible to use a lowpass-filter for noise shaping [10].

4. Measurement Results

Fig. 2 a) Output signal of the C/V \( (V_s) \) in the sense loop. b) Sinusoidal output signal \( (V_D) \) of the drive resonator. c) Digital output signal \( (V_O) \) visible as bitstream of the sense loop. d) Modulation clock \( (V_m) \) used by \( m_1 \) \( (f_{\text{mod}}=9.27 \text{ kHz}) \). e) Measured spectrum of the readout loop.
In Fig. 2 a-d) signals of the drive and sense loop are shown. The output voltage $V_s = 1.1$ V of the sense C/V is shown in Fig 2. a), this voltage corresponds to a residual movement of the sense mass of approximately 5nm around the idle position. The quantization-noise is shaped in the base-band, thus the Coriolis-signal is detectable within a bandwidth of 40 Hz as shown in Fig. 2 e). The modulated readout system is characterized together with a MEMS gyroscope on the rate table as shown in Fig. 3 a). Angular rates are applied. The measured output signal is highly linear with a DC non-linearity of 0.83% over the full-scale (FS) of ±600 °/s, as shown in Fig. 3 b). The complete readout system operates with an $f_c = 9.27$ kHz, which is equal to $f_{Drive}$. This frequency is also used for the comparator and the digital part of ΔΣ-modulator, offering the possibility to enormously reduce the requirements for the analog circuitry and the power consumption in the digital domain.

Fig. 3. a) Hybrid implementation environment based on FPGA, Front-end ASIC and MEMS gyroscope is shown. b) Rate table characterizations reveal a linear full-scale range of ±600°/s. The DC non-linearity of the system is 0.83% FS.

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