A Novel Architecture for Digital Control of MEMS Gyros

H. Rödjegård, D. Sandström, P. Pelin, M. Carlsson[*], M. Bohman[*], N. Hedenstierna[+] and G. I. Andersson

Imego AB, Arvid Hedvalls backe 4, Göteborg, Sweden, henrik.rodjegard@imego.com

[*]Catena Wireless Electronics AB, Kista, Sweden

[+]SensoNor AS, Horten, Norway

Abstract

This paper describes a system for implementation of digital feedback loops and digital signal conditioning to control vibrating MEMS gyroscopes. Compared to conventional analogue solutions this implementation improves the flexibility regarding algorithms and control parameters. The offset stability is also improved since the baseband processing is performed in the digital domain and is thus free from 1/f noise. The algorithms for the digital control loops and the output signal generation are implemented in an FPGA that is connected to the gyro via an interface circuit. This circuit is a configurable analogue ASIC containing high performance capacitive readout amplifiers, ΣΔ-modulators and analogue feedback recovery circuits. An evaluation platform based on the digital concept and PC software has been fabricated. Due to the programmability, the platform significantly speeds up the development process of new algorithms and control parameters. It is also a valuable tool when testing new gyro elements. Until now the system has been evaluated with two different butterfly gyros presently with a lowest resolution of 0.005 deg/s/√Hz. However, it can be used with other capacitive/electrostatic gyros as well.

Keywords

Gyroscope, Delta-sigma converter, Digital control, Development platform

INTRODUCTION

Most vibrating gyroscopes operate at two resonant modes requiring closed-loop control for optimum performance. One loop controls the oscillation of the excitation mode, while the other adjusts the bandwidth of the gyroscope by controlling the Q-value of the detection mode [1]. Further, some gyros utilize frequency matching of the two modes by the introduction of electrostatic negative spring constants. A mixer is also required to demodulate the detected signal. Traditionally, this functionality has been implemented with analogue electronics, either discrete or integrated. An analogue implementation is not very flexible since the architecture is fixed. Development of new algorithms and parameter optimisation is thus often time consuming and expensive. Another problem with an analogue implementation is the signal drift caused by low frequency noise in the analogue circuitry after the signal is mixed down to DC.

Thanks to the performance of higher order ΣΔ-modulated A/D converters [2], the gyro oscillation signals can be A/D converted with high resolution. Analogous, digital ΣΔ-modulators can be used to D/A convert the feedback signals to the gyro, which allows the control loops and the mixers to be implemented with digital electronics. The advantages

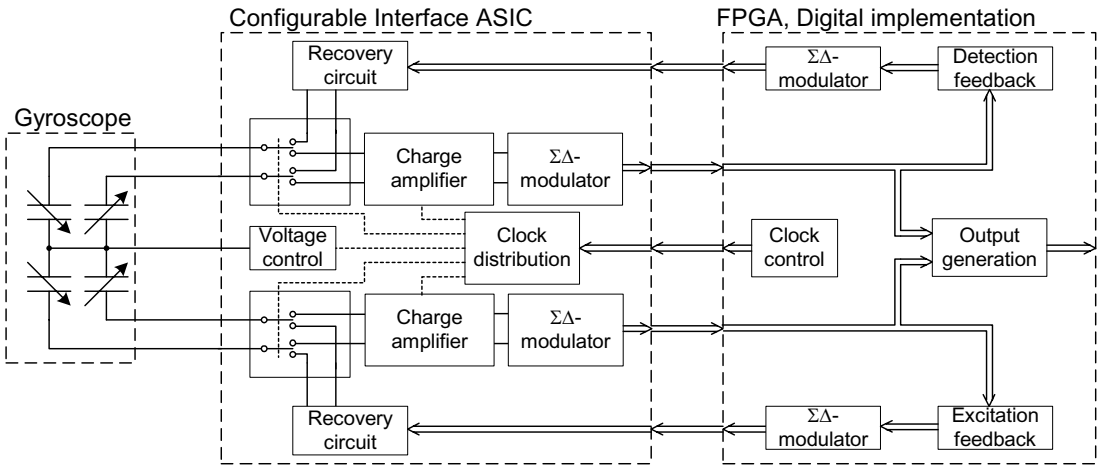

Figure 1. The architecture of the digitally controlled gyroscope.

with that technology are not only increased flexibility and improved trimming opportunities, but also improved performance since more complex algorithms can be utilized and since no low frequency noise affects the signal after the digital mixers.

In order to explore digital control of MEMS gyros and to boost the development process of the next generation gyro systems, an interface ASIC and a development platform have been developed as a joint project between the Imego Institute, SensoNor AS, Saab Bofors Dynamics AB and NFFP (the national flight research programme in Sweden). The large number of actors put high requirements on the flexibility of the system. It should operate with different gyroscopes, commercial as well as research prototypes, with different sensitivities and operating frequencies. Furthermore, the system resolution should be limited by the sensor elements, and not by the electronics.

SYSTEM ARCHITECTURE

The system is mainly designed to operate with two different sensing elements, the Imego developed Munin gyro and the sensing element of the commercial SAR10 gyroscope developed by SensoNor. The Munin gyro is a bulk micromachined gyro operating at about 2.5 kHz with 16 pF detection capacitors in parallel with parasitic capacitors of about 100 pF. The SAR10 sensor elements are much smaller than the Munin gyro since its thickness is only a fraction of the wafer thickness. It operates at a significantly higher frequency and the detection capacitor values are much lower. For both gyroscopes the k_BT/C-noise in the capacitance detection should be the limiting factor for the resolution of the whole system. Further, the measurement frequency should mainly be limited by the RC-constants of the gyro. The architecture of the system is outlined in Figure 1, and a top view of the ASIC is shown in Figure 2. The size of the circuit is 3 mm x 3.2 mm.

The interface ASIC contains many blocks controlled by clock signals. Therefore, the clock distribution has been designed to emit as little substrate noise as possible. A great effort has also been spent on the ΣΔ-modulator, since the data streams are semi-stochastic and might generate noise when folded by the measurement circuitry.

The control loops, the demodulation circuitry, filtering and timing are implemented as a digital configuration of the FPGA. The interface ASIC and the FPGA communicate through digital 1-bit ΣΔ-modulated signals. The interface ASIC is built up from two identical signal paths, one for the excitation loop and one for the detection loop. Each loop consists of a charge amplifier, a ΣΔ-modulator, a digital feedback implementation with a ΣΔ-modulated feedback signal and a recovery circuit for the feedback signal.

Charge amplifiers

The charge amplifiers are fully differential charge integrators using the correlated double sampling technique further described in [3]. The differential amplifiers are designed to have an equivalent input noise of 2 nV/√Hz and a gain bandwidth product of 30 MHz. The gain of the charge amplifier is determined by integration capacitors, which are programmed via a serial bus interface at start up. The capacitors can be adjusted between 0.7 pF and 22.4 pF in steps of 0.7 pF.

ΣΔ-modulators

The analogue ΣΔ-modulators are designed to have an equivalent input noise level lower than 50 nV/√Hz in the frequency range between 2 kHz to 15 kHz. The outputs are 2 MHz single bit data streams with voltage levels according to the LVDS-standard.

Voltage control circuit

The voltage control circuit applies the voltage steps that are required for the correlated double sampling. It also applies the required bias voltage to the gyro mass during the force feedback phase.

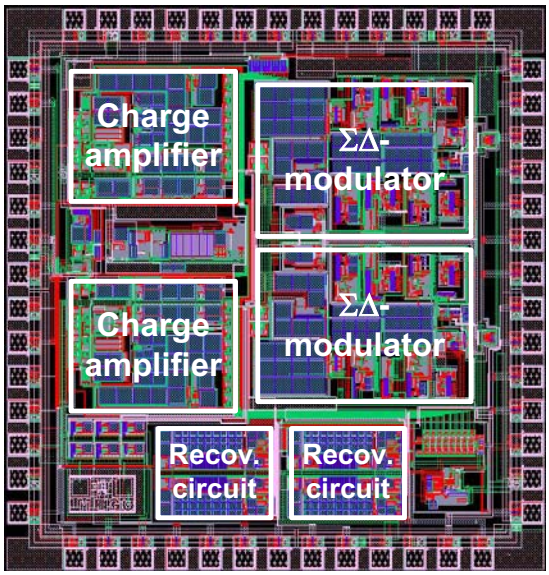

Figure 2. Top view of the interface ASIC.

Recovery circuits

The digital feedback signals are sigma delta modulated data streams. In order suppress the noise from the digital supply voltage the feedback data streams are level-shifted by the recovery circuits. The recovery circuits also low-pass filter the data stream to avoid the high frequency ΣΔ-noise to be folded down to the gyro frequency. The filter is implemented in a way that minimizes offset and drift. The corner frequency is designed to be 40 kHz.

DIGITAL IMPLEMENTATION

The digital signal processing consists of three main blocks, the excitation feedback, the detection feedback and the output generation. All blocks have in common that they work only on the necessary bit width and part of the algorithms even operates directly on the ΣΔ bit stream.

The purpose of the excitation feedback loop is to make sure that the excitation mode oscillation has constant amplitude. This is done using a digital counterpart of an analogue Automatic Gain Control circuit. The detection feedback algorithm makes sure that the bandwidth of the detection mode, and thus the rate signal bandwidth, is increased. It also desensitises the sensor for changes in Q factor of the detection mode. Both control loop algorithms contain digital ΣΔ modulators, which output ΣΔ bit streams back to the ASIC's recovery circuits.

The output generation block performs the mixing and low-pass filtering of the excitation and detection signals to generate a rate signal. The mixing is done directly on the detection mode ΣΔ bit stream, which causes the rate signal to have a significant amount of quantisation noise in high frequencies. Therefore, low-pass filtering is performed by a decimation filter.

TEST PLATFORM

The purpose of the test platform, shown in Figure 3, is to test the digital concept as well as serving as a demonstration and development unit. It contains an FPGA for the signal processing algorithms and a microcontroller for controlling the external interfaces. A single-line display, which can show the rate in real-time, and push-buttons constitute the human interface. The test platform is configured via the USB and JTAG interfaces. There are also general digital data buses and three analogue connectors, which are used to collect data during testing.

Figure 3. The gyro test platform.

The parameters of the signal processing algorithms can be changed on the fly via the USB interface. This gives the user the opportunity to investigate the sensor behaviour with different algorithm settings and optimise the parameters.

TEST RESULTS

Testing has been performed with two different sensing elements, the Munin gyro and the SensoNor SAR10 gyro, see Figure 4. The Munin gyro prototype suffers from a lower than expected Q factor in the excitation mode, and can thus not be driven to the desired oscillation amplitude. Nevertheless, the noise density has been measured to 0.013 deg/s/√Hz, a number which is expected to decrease with an order of magnitude when using high-voltage excitation. The corresponding figure for the system with the commercial SAR10 element is 0.005 deg/s/√Hz.

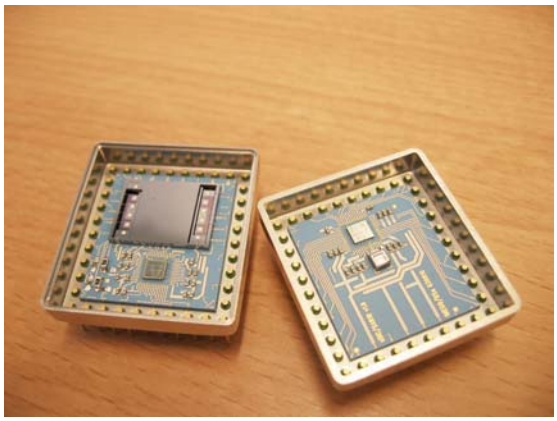

Figure 4. The two different MEMS gyroscopes mounted with interface ASICs on LTCC substrates.

Figure 5 shows the rate signal from the SAR10 sensor element with the digital control during characterisation on a rate table. The rate is linearly ramped up to 100 deg/s and down to 0 deg/s.

Since the baseband signal processing is performed in the digital domain, no 1/f noise components could be seen during the measurements. The high stability allows measurements to be performed at very low frequencies with high accuracy, or for long time periods without bias drift. As a result, the earth rate (15 deg/h) modulated at 0.05 Hz has been measured with the SAR10 element. The modulation was achieved through a rotation of the system around an axis orthogonal to the sensitive axis with a constant angular rate of 3 rpm, causing the sensitive axis to successively change between north and south.

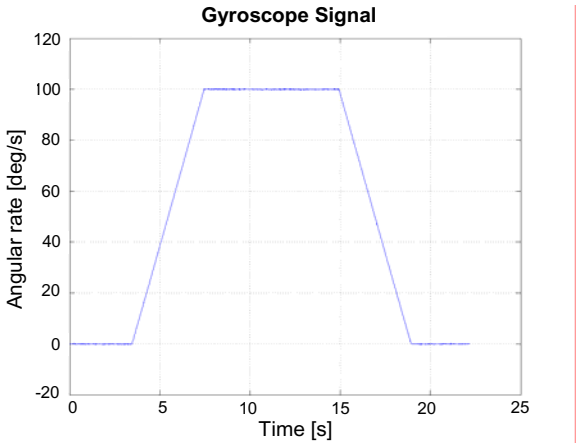

Figure 5. Rate signal from the SAR10 gyro with digital control.

CONCLUSIONS

The concept of digital control of gyroscopes has been evaluated with a programmable platform that can be adopted for several different MEMS gyroscopes. A programmable interface ASIC has been fabricated. The ASIC contains the necessary circuitry for excitation and readout of capacitive/electrostatic gyroscopes. The ASIC communicates with the digital circuitry with ΣΔ-modulated 1-bit data streams. The feedback loops and the signal extraction are implemented in an FPGA which allows a great amount of flexibility.

Tests have shown that the platform can be programmed to operate with different MEMS gyroscopes. Algorithms for the feedback loops have been developed and implemented. The system does not only offer flexibility, but also good stability of the gyro signal since the analogue low-frequency noise does not affect the signal.

Until now a best resolution of 0.005 deg/s/√Hz has been achieved using a small low-cost commercial sensor element aimed for the automotive industry.

REFERENCES

[1] G. I. Andersson et al., "A Novel Silicon Bulk Gyroscope", *Proc. of Transducers 1999*, pp. 902-905.

[2] S. R. Norsworthy, R. Schreier and G. C. Temes, *Delta-Sigma Data Converters*, IEEE Press, New York, 1997.

[3] B. E. Boser, "Capacitive Interfaces for Monolithic Integrated Sensors", *RF Analog-to-Digital Converters; Sensor and Actuator Interfaces; Low-Noise Oscillators, PLLs and Synthesizers*, Kluwer Academic Publishers, November, 1997.