



Introduction

Productivity Engineering (PE) IC Design GmbH is a Customer Specific Integrated Circuit design service provider. Services provided are specification development, feasibility studies, consulting and finally the development of digital and analog / mixed signal IP (Intellectual Property) building blocks and full custom integrated circuit design. The latter involves everything up to layout and tape out. In close cooperation with the parent company the full IC supply chain management including test, packaging and production planning is being provided.

Mixed-Signal ASICs are being used everywhere when an Interface between digital sensor signal conditioning of any kind and the real world is needed. The real world signals that sensors capture are very much of an analog nature.

This paper describes a method to capture analog sensor signals provided by micromechanical sensors (MEMS) with a very high resolution while avoiding the typical hassle of analog-to-digital conversion, noise and offset minimization techniques and trimming procedures.

Classical systems are presented at first. The second part of this paper presents the PE-MEMS-ASIC solution.

Classical Sensor Signal Capturing Methods

Capturing environmental conditions caused by a capacitance change of a sensor usually have high requirements in the quality of the used circuit structures. The basic requirements are:

- Relatively small capacitance changes have to be recognized
- Independency of other parasitic elements such as resistance of sensor wires or offset capacitances
- Independency of temperature and supply voltage changes
- Independency of parasitic capacitances
- Repeatability of measurement results
- High reliability and yield
- Certain independency of the manufacturing process

Traditional methods of sensor signal capturing can be separated into the following groups:

- DC circuits: The sensor capacity will be charged by an RC circuit to a certain DC level. Changes in capacity which are well beyond the maximum frequency of the RC circuit can be captured as a voltage change on the sensor.
- RC, IC and LC oscillators: The sensor capacity defines the frequency within the oscillating circuit. Changes of the sensor capacity are directly related to changes of the oscillator frequency and thus can be captured digitally.
- Impedance measurement circuits (e.g. synchronous demodulator): The sensor capacity will be stimulated by an AC voltage. By using the stimulating signal along with the sensor manipulated same signal a demodulation can be accomplished (e.g. amplitude modulation). Disturbing signals can be suppressed significantly this way.

The listed methods have very different characteristics and are partially very limited in their properties for integrated circuit implementation. Generally it can be said that the achievable results in sensor signal measurement strongly depend on the quality of the used analog circuit architecture and related technology properties. Each of the methods requires a very accurate reference. The quality of the reference is a measure for the quality of the total system quality. High performance circuits (resolution >8bit) usually require a reference calibration.



Methods for resolution improvements in sensor signal capturing

Common trends in sensor signal conditioning circuit design is to translate the efforts from the analog into the digital circuit part of such a system. This way the characteristics of a relatively simple logic system can be better predicted and simulated than in a more analog approach.

Classical measurement engineering employs Sigma-Delta converters. The basic concept of this conversion is to make rough evaluations of the signal, to measure the error, integrate it and then compensate for that error. This way the total error is reduced. The mean output value is then equal to the mean input value if the integral of the error is finite.

A high over-sampling rate well beyond the Nyquist rate is needed. When a signal is quantized, the resulting signal approximately has the second-order statistics of a signal with independent additive white noise. This means it is equally distributed over the whole frequency range. It can be filtered by a low pass filter. Employing modern CMOS technologies for the integrated circuit structure quantization of the input signal can be very low, thus reducing requirements in analog circuit design. This technique has been used for several years now but ever since the requirements prior to the converter on the sensor interface is still very high. Systematic errors caused by simple physics of the purely analog circuits are still part of the output signal after conversion. A solution is to take a view at the sensor and the circuitry as a whole unit and to make use of the sensor properties in the integration with the circuitry. Result of this approach will be a sigma-delta modulator that integrates the sensor as a relevant part in signal conditioning.



Sensor signal capture methods with feedback loop

Purpose of a feedback loop in any sensor circuit is to manipulate the characteristics and noise behaviour of the sensor element. None of the former methods can make good use of such a feedback loop. Further methods can do that in a much better way.

Well known property of a feedback loop system is the replacement of the characteristic curve of the sensor by the characteristic curve of the feedback path having a gain much larger than one. This causes the following improvements:

- Linear system characteristics
- Independence of manufacturing tolerances, power supply and temperature
- Reduction of aging properties of the sensor

Most important in this context is the linearization of the sensor characteristics curve. Pressure and acceleration sensors have their basics in mechanical properties like spring constant. These properties depend on manufacturing process tolerances to a large extent. Consequently linear system behaviour can not be guaranteed as it is needed for a high resolution sensor system. If it would be possible to integrate the system with a feedback loop with good control over the characteristics of that loop the sensor behaviour could be improved and a much higher resolution of the sensor signal system would be feasible.

Potential improvements of the system behaviour:

- Frequency response linearization
- Bandwidth increase of the system
- No resonance in micromechanical systems
- Reduction of the noise level of the sensor system
- Higher stability of the system

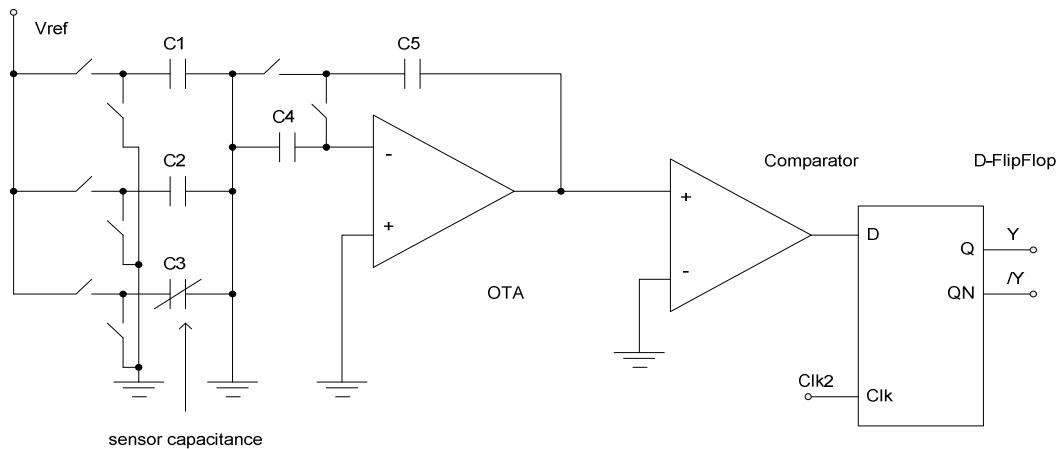
Sigma-Delta Modulator in a Micro Mechanical System

Generally the Sigma-Delta Modulator is being used for A-to-D conversion. The feedback loop that is a part of such a converter is usually seen as a pure electrical part. Taking a view of the feedback loop in a Micro-Electro-Mechanical System (MEMS) allows for new system behaviour.

In a sigma-delta conversion resolution and sampling rate can be replaced for each other. Using a high over sampling rate (OSR), requirements on quantization can be reduced. Furthermore quantization noise is reduced by the loop filter while moving the noise out of the actually interesting signal bandwidth.

Tasks are being shifted from the value and time continuous analog domain into the value and time discrete digital domain.

Example for a sigma-delta modulator for a pressure or humidity sensor system:



In the above picture a switched capacitor amplifier followed by a quantization structure is being used for capturing a capacitive sensor signal. The structure basically employs all properties of a Sigma-Delta Modulator. Charge on the capacitors is being counted.

A comparison of the sensor capacity charge (C3-C2) against a reference capacity charge (C1) builds the base for the system. The system is being clocked while accounting for the comparator results.

The result is a data stream at the frequency of Clk2. Statistical property of the data stream is a measure for the ratio of the sensor and reference capacitance. Reference and offset capacity can be designed to be programmable by a capacitive DAC. This way the system can account for different sensors. Reference capacity can also be a part of the sensor itself. Other configurations are feasible. By calibration of the circuit (change injection error, offset and reference capacity) a resolution of real 20 bit is feasible. The system performance does not depend on the parameters of the OTA or the comparator.

PE MEMS-ASIC : Sigma-Delta converter in a MEMS for force feedback

The proposed ASIC approach is to keep the sensor in its natural position by employing the feedback loop in the sense of a force feedback. The mechanical force receives a compensating resistance that keeps the sensor element from moving. Information about the measurement signal is not lost because the originating force is being transformed into an opposite force. This opposite force can be measured. Limitation or even avoidance of the mechanical movement of the sensor causes:

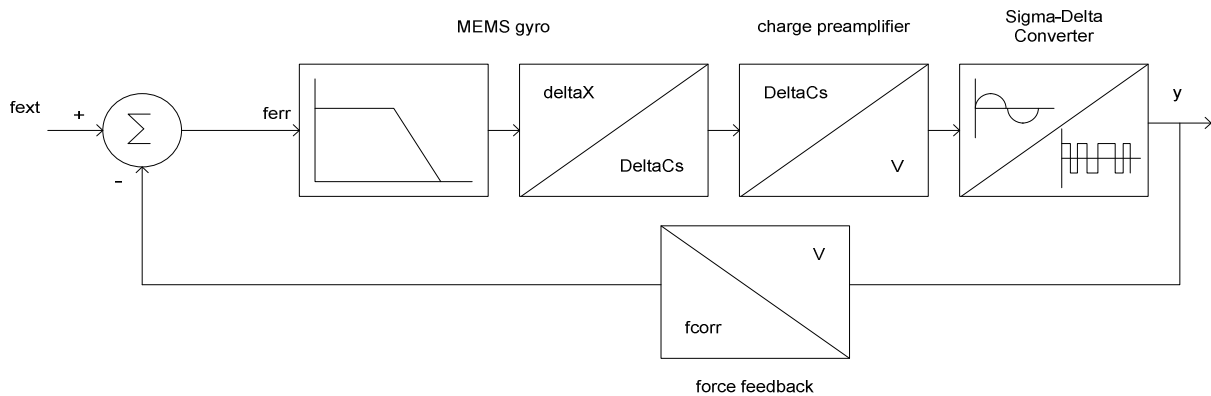
- Linear relation between cause and effect
- higher dynamic range because maximum deflection of the sensor is not a limiting factor
- higher sensor bandwidth

The mechanical inertia having a low pass characteristics can be used in the signal conditioning circuitry, e.g. in the loop filter of a sigma-delta converter. Combination of high resolution converter architecture with a force feedback sensor system can achieve an extremely high quality factor. By using the sensor in feedback sigma-delta architecture it is sufficient to provide the correction voltage according to the force to the sensor capacitor. The measurement result is again a statistical calculation of the output signal of the sigma-delta modulator. Assuming clock and amplitude of the feedback is constant with time, the system has a very linear system characteristics.

Basic advantages of such architecture are:

- **robust against semiconductor manufacturing process variations**
- **relatively low requirements in circuit design efforts**
- **low requirements in accuracy of analog circuit structures**

Sigma-Delta Modulator with force feedback:



Force feedback loop acceleration MEMS system:

