SIGMA-DELTA MODULATION AND BIT-STREAM PROCESSING FOR SENSOR INTERFACES

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The sigma-delta technique is pretty convenient for realizing high performance sensor interfaces. This technique, indeed, besides the conventional benefits produced by oversampling, allows the straightforward implementation of several simple linear and non linear processing operations, useful in the correction of the non-idealities of low frequency sensor signals.

1 Introduction

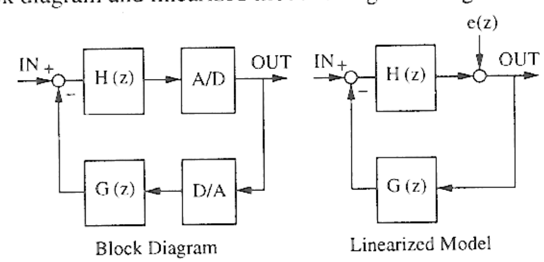
The output signal of an integrated sensor is an electrical variable (voltage, current, capacitance or resistance), whose bandwidth is often small. Typically, the signal level is quite low and degraded, thus requiring amplification, linearisation, compression or expansion, and linear combination with other signals.

Sigma-delta modulators are recognised to be the best approach for analog-to-digital conversion of narrow band signals[1]. This technique allows us to trade speed with accuracy. Therefore, in view of the limited bandwidth of most sensor signals, it is possible to achieve good accuracy at a reasonable operating speed, without using precise components. A single bit quantiser is used to convert the analog signal into a bit-stream, which can be processed and combined with other signals (either analog or digital), without requiring complex digital circuitry.

2 Sigma-Delta Modulation

Fig. 1 shows the general structure of a sigma-delta modulator. Blocks $H(z)$ and $G(z)$ are designed to achieve a unity transfer function for the signal:

Fig. 1 Block diagram and linearized model of a generic sigma-delta modulator



$S(z) = z^{-p}$ (pure delay) and a high-pass transfer function for the quantisation noise: $N(z) = (1 - z^{-1})^L$, where L is the order of the modulator. For a first-order modulator, $H(z) = z^{-1} / (1 - z^{-1})$ (integrator with delay) and $G(z) = 1$. In general, the input stage is an integrator also for higher order modulators.

The output signal of a sigma-delta modulator is a bit stream, i. e. a sequence of binary digits (1 and 0), without positional information. A bit-stream is an intermediate domain for signal representation, which combines analog and digital characteristics. The spectrum of a bit-stream consists of the spectrum of the analog signal plus the quantisation noise, which is shaped in the frequency domain to reduce the in-band total noise. In conventional sigma-delta A/D converters, the bit-stream is low-pass filtered and decimated in order to obtain a multi-bit digital signal at Nyquist rate (twice the bandwidth of the analog signal). The accuracy of the converter can be increased by increasing the modulator order or by increasing the oversampling ratio[1].

Once that signals are converted in digital domain, they can be processed by a digital processor. However, this conventional approach requires a non-negligible silicon area for the decimation filter and the signal processor. In the next section we will see show that this problem can be overcome by performing some operations directly on bit-streams.

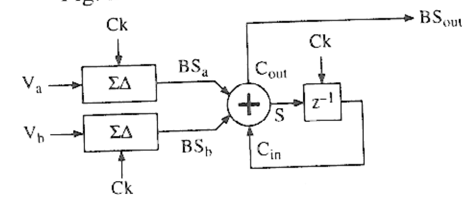
3 Simple Operations on Bit-Streams

In this section we discuss how to add, subtract and multiply bit-streams, and how to compensate non-linear response of sensors.

In a bit-stream the information is coded in pulse density modulation (PDM) format. Assuming the input dynamic range of the sigma-delta modulator to be $[V_L, V_H]$, an output bit sequence containing N_1 1's and N_0 0's corresponds to an analog input signal $V = V_L + (V_H - V_L) \cdot N_1 / (N_1 + N_0)$. A sequence containing only 0's corresponds to the lower bound of the input range (V_L), while a sequence containing only 1's corresponds to the upper bound (V_H). It is, therefore, evident that complementing a bit-stream is equivalent to reversing the input range. Moreover, if the input range is symmetrical ($[V_L, V_H] = [-V_{max}, V_{max}]$), the bit-stream complement is equivalent to the multiplication by –1 of the input signal.

In conventional digital circuits, the addition of two bits produces a 2-bit word, which means an increase in complexity. Another simple solution is to perform addition through interleaving, which merges two bit-streams by duplicating the oversampling frequency. However, it is possible to re-shape a multi-bit word, thus obtaining a bit-stream at the same sampling rate[2]. This

Fig. 2 Addition of two bit-streams



operation can be done by the circuit shown in Fig. 2: a full adder performs the addition of the two bit-streams, and the output bit-stream is taken from the carry-out. The output bit-stream BS_{out} corresponds to the analog signal $V_{out} = (V_a + V_b) / 2$. The same circuit can be used to obtain the difference of two signals, simply by inverting V_b.

Multiplication of bit-streams is also straightforward[3]. Indeed, the product of two single-bit signals can be obtained with just one logical gate: an 'AND' if the analog input range is $[0, V_{max}]$ or an 'XNOR' if the analog input range is $[-V_{max}, V_{max}]$. However, this approach affects the noise-shaping characteristics. Indeed, multiplication in time domain corresponds to convolution in z-domain. Therefore, the resulting bit-stream has four components: one from the convolution of the two signals $(S_1(z) * S_2(z))$, two from convolutions between one signal and the shaped noise of the other bit-stream $(S_1(z) * N_2(z) + N_1(z) * S_2(z))$, and the last from the convolution of the two shaped noises $(N_1(z) * N_2(z))$. Since the last term has a flat frequency spectrum, the result of a multiplication of two noise-shaped bit-streams is a non noise-shaped waveform, whose in-band noise limits the accuracy of processing[4].

To avoid this drawback, a mixed-signal multiplication scheme can be used. The input signal V_b is converted into a bit-stream, which is multiplied by V_a. Then the resulting signal is passed through a sigma-delta modulator to obtain the output bit-stream, as shown in Fig. 3. When the signal V_b has a single

Fig. 3 Bit-stream multiplication of two signals

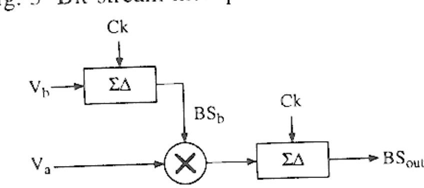
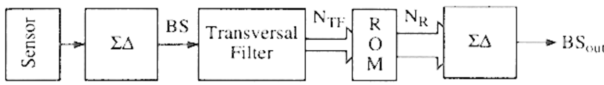


Fig. 4 Scheme of the calibration on a sensor output



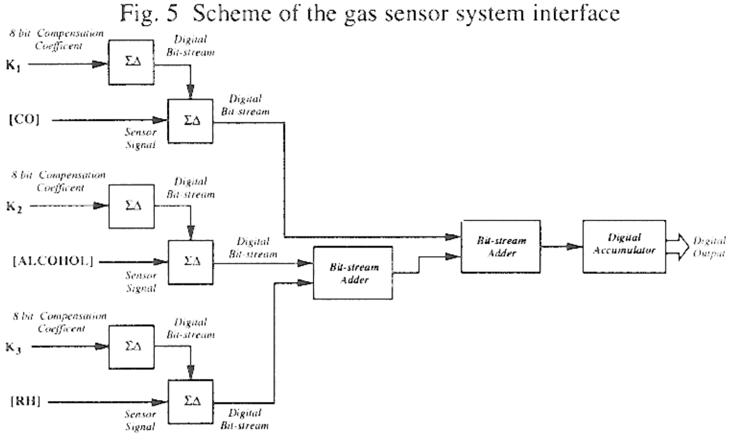
polarity range $[0, V_{max}]$, the multiplication block in Fig. 3 can be implemented with an 'on-off' switch. If V_b has a symmetrical range $[-V_{max}, V_{max}]$, then the product is made by switching between V_a and $-V_a$. In switched-capacitor implementations, this can be done easily by controlling the phases of switches[3].

Non-linearities in sensor output can be corrected with a calibration in the digital domain[5]. Fig. 4 shows a scheme employing a ROM to store calibration coefficients. The sensor output is converted into a bit-stream by a sigma-delta modulator. The bit-stream is low-pass filtered to achieve a digital word with N_{TF} bits, which is used as address for the ROM. The ROM output is a word with N_R bits, which can be processed in digital domain or converted back to a bit-stream by means of a digital sigma-delta modulator.

4 Examples of Sigma-Delta Interfaces for Sensors

The operations described in the previous section can be combined to obtain very compact and efficient signal processing chains for sensor interfaces. Examples are a tri-phase energy meter for power lines[6], a RMS voltage converter[7], and a gas sensor system for carbon monoxide detection[8].

Fig. 5 Scheme of the gas sensor system interface



The latter example is illustrated by the block diagram in Fig. 5. Since the CO sensor is intrinsically sensitive to interfering gases (alcohol and humidity), a multi-sensor system is used to achieve the required selectivity. Output signals from three sensors, multiplied by suitable coefficients (K_1, K_2 and K_3), are converted into bit-streams and added to obtain a single signal, proportional to the CO concentration. Multiplications and additions are realized using the techniques described in Sect. 3.

5 Conclusion

Sigma-delta modulators can be conveniently used to implement sensor interfaces. Their simplicity and tolerance to process variations make them suitable for processing analog signals also in non conventional technologies. Moreover, simple linear and non-linear processing of bit-streams can be realized with minimum area and without the need of multi-bit digital processors.

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