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DAC Waveform Effects in CT Incremental $\Sigma\Delta$ ADCs for Biosensor Applications

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Abstract—Incremental sigma-delta ($\Sigma\Delta$) analog-to-digital converters (ADCs), which are essentially $\Sigma\Delta$ ADCs with periodic resetting, are well suited for low-power low-speed biosensor applications. In recent years, the potential advantage in terms of power dissipation of continuous-time (CT) $\Sigma\Delta$ ADCs have been explored. This paper analyzes the impact of feedback digital-to-analog converters (DACs) on the performance of CT $\Sigma\Delta$ ADCs. Different feedback DAC schemes are firstly analyzed and then evaluated by employing them in a 3rd order single-bit CT $\Sigma\Delta$ ADC. Simulation results are discussed considering the trade-off between the timing error sensitivity and the power consumption, thereby offering a reference for selecting a power efficient feedback DAC scheme.

I. INTRODUCTION

Unlike conventional $\Sigma\Delta$ ADCs that process input signals continuously, incremental $\Sigma\Delta$ ADCs reset their memory elements before each conversion, and hence can offer sample-by-sample conversions as Nyquist-rate ADCs [1]. Historically, incremental $\Sigma\Delta$ ADCs have been developed for instrumentation and measurement (I&M) applications. Among these applications, biosensors, which typically feature a low frequency input signal from a few hertz to a few kilo hertz [2], is a recent research hot spot. Compared with traditional I&M applications, biosensors are more power-constrained since they are mostly powered by small battery or even self-powered by harvested energy.

Majority of the published works on incremental $\Sigma\Delta$ ($\Sigma\Delta$) ADCs employ discrete-time (DT) loop filters. Only recently, continuous-time (CT) implementations have been explored, with the aim of reducing the power consumption. Similar to traditional CT $\Sigma\Delta$ ADCs, CT $\Sigma\Delta$ ADCs have relaxed settling and bandwidth requirements on their integrators [3]. As in the CT $\Sigma\Delta$ ADCs, the CT $\Sigma\Delta$ ADCs suffer from similar design challenges, e.g., the increased sensitivity to nonidealities in the feedback DACs compared with their DT counterparts. The most critical DAC nonidealities are timing errors that alter the width and position of the feedback DAC waveforms, known as clock jitter and excess-loop-delay (ELD) [4].

In literature, there are theoretical and experimental analysis on the DAC timing error sensitivity of CT $\Sigma\Delta$ modulators [5–9]. However, for low-power low-speed applications, CT $\Sigma\Delta$ ADCs have specific challenges which need to be addressed and analyzed. Firstly, even for the relatively low sampling frequency used in these applications, the tolerance range of

timing error in feedback DACs needs to be identified to ensure a robust design. Moreover, the resetting operation in $\Sigma\Delta$ ADCs would introduce some issues and differences compared with the $\Sigma\Delta$ ADCs. Most importantly, the power consumption is a big concern in biosensors and thus some design trade-offs should be considered.

In this paper, the sensitivity to timing errors of representative feedback DAC schemes in CT $\Sigma\Delta$ ADCs are analyzed. Additionally, their impact on speed and bandwidth requirements for the active blocks in the modulator are examined. The paper is organized as follow. Section II introduces the feedback DAC schemes included in this study. The sensitivity to jitter and ELD is analyzed, and the differences induced by the incremental mode of operation are illustrated. The impact of various DAC schemes on the 1st integrator are also presented. In section III, a CT $\Sigma\Delta$ ADC, which employs different DAC schemes, is simulated using Matlab/Simulink and Verilog-A models. These results are compared and discussed considering low-power low-speed biosensor applications. Section IV finally concludes the paper.

II. DAC NONIDEALITIES IN CT $\Sigma\Delta$ ADCs

The 3rd order single-bit CT $\Sigma\Delta$ ADC [3] given in Fig. 1 is used as a demonstration vehicle for this analysis. The input signal is sampled at the rate of f_S/M and then held for the entire conversion cycle, $T_S \times M$. The modulator runs at the clock rate of f_S and its integrators are reset every M clock cycles. At the end of each conversion, the modulator output is digitized by the digital filter which is also reset every M clock cycles. Here, the number of clock cycles in each conversion, M , is equivalent to the oversampling ratio (OSR) in conventional $\Sigma\Delta$ ADCs.

The sensitivity to clock jitter is one of the most significant DAC nonidealities from which the CT implementation suffers. The jitter sensitivity depends on the waveform of feedback DAC scheme, as shown in Fig. 1. The selected feedback DACs can be divided into two categories: the commonly used rectangular DACs including non-return-to-zero (NRZ), half-return-to-zero (HRZ), and return-to-zero (RZ) [5]; and the exponentially decaying DACs including switched-capacitor-resistor (SCR), full clock period SCR (FSCR), and switched-capacitor switched-resistor (SCSR) [6–8]. For a single loop CT $\Sigma\Delta$ modulator with a single-bit DAC, the jitter induced

Fig. 2. Impact of the resetting cycle on DAC waveforms with jittered clock. (a) modulator output with resetting, and (b) erroneous feedback of NRZ DAC.

of the DAC is larger than the variation of the clock jitter, the aforementioned error can be avoided for all DAC schemes.

It is also worth mentioning that in most cases the $\Sigma\Delta$ ADC achieves lower signal-to-quantization-noise-ratio (SQNR) than traditional $\Sigma\Delta$ ADC. It has been illustrated in [10] that an $\Sigma\Delta$ ADC has higher in-band quantization noise than a $\Sigma\Delta$ ADC with the same modulator order and OSR. The increased quantization noise floor in the incremental case, in turn, relaxes the requirement on jitter and ELD induced IBN.

As it can be indicated from Eq. (1), the charge injected by the exponentially decaying DACs is less sensitive to clock jitter. However, we can appreciate from Eq. (2) that their feedback coefficient a_1 would be significantly larger than for rectangular DACs to transfer the same amount of charge. The increased coefficient gives rise to a linear error if the integrator has finite gain bandwidth (GBW); a non-linear error when the integrating op-amp is slew-rate (SR) limited. The integrator gain error (GE) induced by finite GBW and the minimum required op-amp SR can be respectively expressed as [4,6]:

$$GE = \frac{GBW}{(a_1 + b_1) \cdot c_1 \cdot f_S + GBW}, \quad (5)$$

$$SR \left[\frac{V}{S} \right] \geq f_S (b_1 \cdot c_1 \cdot u + a_1 \cdot c_1 \cdot V_{ref}), \quad (6)$$

where u is the input signal amplitude and V_{ref} is the DAC reference voltage. It can be appreciated from Eq. (5) and (6) that the larger the feedback coefficient a_1 is, the higher GBW and SR requirements are imposed on integrators.

III. SIMULATION RESULTS AND DISCUSSIONS

The theoretical analysis is complemented by behavioral simulations of the 3rd order 1-bit CT $\Sigma\Delta$ ADC (shown in Fig. 1) where different schemes are employed for the feedback DAC. The modulator is reset before processing each sampled input and then runs continuously for M cycles. Considering a typical biosensor application which features a resolution of 10-bit and an input signal bandwidth of 4 kHz, $M = 40$ is chosen in simulations. The CT loop filter coefficients c_1 , c_2 and c_3 are derived for different feedback DACs by using the impulse-invariant transformation (IIT). For each DAC scheme, IIT is also used to obtain the transfer function of the digital filter, $DF(z)$, following the method described in [3].

The DAC's sensitivity to timing error and its impact on the signal-to-noise-and-distortion ratio (SNDR) performance

Fig. 3. Simulated SNDR of the CT $\Sigma\Delta$ ADC under the influence of timing errors. (a) SNDR vs. τ_d , (b) SNDR vs. σ_j , and (c) SNDR vs. σ_j for $\tau_d = 10\%T_S$. [$\times$:RZ, $\circ$:HRZ, $\square$:NRZ, ∇ :SCR, $\triangle$:SCSR, $\star$:FSCR.]

are evaluated in Matlab/Simulink environment. The CT $\Sigma\Delta$ ADC employing different DAC schemes is firstly simulated under the influence of ELD. As explained in sec. II, τ_d can hardly exceed 10% according to Eq. (3). Fig. 3 (a) shows that no significant variation in SNDR is observed with the τ_d swept up to $10\%T_S$. Thus, ELD does not play a deterministic role in this application. The CT $\Sigma\Delta$ ADC is then simulated under the influence of clock jitter. The amount of jitter is varied in the range of $\sigma_j = 0.0001\%T_S \sim 1\%T_S$, corresponding to $3.125 \text{ ps} \sim 31.25 \text{ ns}$. This root-mean-squared jitter range is readily achievable when the sampling clock is derived directly from crystal oscillators. Fig 3 (b) shows the simulated SNDR with only clock jitter introduced. The significant performance degradation of NRZ, RZ and FSCR DACs has a good matching with the estimation given by Eq. (4). It also presents the same trend of jitter sensitivity as predicted by Eq. (1) for HRZ, SCR, and FSCR DACs. Fig 3 (c) shows the simulated SNDR under the influence of clock jitter for a fixed ELD of $10\%T_S$. As previously analyzed, the error induced by the resetting is eliminated by introducing a certain ELD. It also indicates that the jitter induced IBN begins to dominate the noise contribution when $\sigma_j = 0.01\%T_S$ for RZ and HRZ; $\sigma_j = 0.1\%T_S$ for NRZ; and $\sigma_j = 1\%T_S$ for exponentially decaying SCRs.

To investigate the impact of DAC schemes on integrator nonidealities, the CT $\Sigma\Delta$ ADC with different DACs is modeled in Verilog-A and simulated using Cadence Spectre. Only the 1st integrator is examined here, since it generally consumes the highest power and errors entering this stage are not suppressed by noise shaping. The normalized unity-gain-bandwidth (UGB), DC gain and transconductance needed for the feedback Gm cell ($G_{m,fb}$) in the 1st integrator, assuming a Gm-C implementation (as shown Fig. 1) are presented in Table I. The simulated SNDR under the influence of finite SR of the $G_{m,fb}$ in the 1st integrator are compared in Fig. 4 (a) and (b) for rectangular DACs and exponentially decaying DACs, respectively. Simulation results confirm the previous theoretical analysis by showing that the rectangular DACs impose less design requirements on the 1st integrator compared with the exponentially decaying DACs. Obviously, the price to pay for relaxed requirements, and consequently possible lower power consumption, is the increased sensitivity to timing error, especially clock jitter, according to Fig. 3.

TABLE I
UGB, GM AND DC GAIN IN THE 1st INTEGRATOR FOR DIFFERENT DACS.

Feedback DACs	UGB_{fb}	$G_{m,fb}$	$A_{DC,fb}$
NRZ	$33.51\% \times f_s$	$1.07 \mu S$	78.8dB
RZ/HRZ	$67.03\% \times f_s$	$2.14 \mu S$	84.8dB
SCR	$193.42\% \times f_s$	$6.19 \mu S$	94.1dB
FSCR	$150.66\% \times f_s$	$4.82 \mu S$	91.9dB
SCSR	$77.25\% \times f_s$	$2.47 \mu S$	86.1dB

Fig. 4. Simulated SNDR with varying op-amp SR of the $G_{m,fb}$ in the first integrator. (a) rectangular DACs, and (b) exponentially decaying DACs.

As an example, the power spectral density (PSD) for each DAC scheme is presented in Fig. 5, where nonidealities (i.e., ELD, clock jitter and SR) are introduced for each case. While the ELD and clock jitter show their timing error sensitivity, the SR determines the biasing current needed in the op-amp, which is an indicator of power consumption. RZ and HRZ are the most sensitive to clock jitter while their SR requirements are slightly higher than for NRZ. SCR imposes the most stringent SR requirement, which may not be very attractive option for this power-constrained application. SCSR achieves a good trade-off between timing error sensitivity and SR requirement, however, the complexity of its circuit implementation would introduce extra power consumption. In terms of timing error immunity, FSCR is the best, however, the speed requirement is the highest. In general, for the relatively low speed biosensor applications, NRZ appears a good candidate due to its best power efficiency. The target resolution is obtained with very low requirements on the 1st integrator and acceptable clock jitter values. In addition, a NRZ feedback DAC can be easily implemented with standard circuitry. The resetting induced error can be avoided, for instance by guaranteeing a certain ELD. Using NRZ DAC results in inter-symbol interference (ISI) in traditional CT $\Sigma\Delta$ ADCs [11]. This is not a problem for the incremental mode, as each sample is converted independently. For the modulator topology shown in Fig. 1 in particular, there is another advantage of choosing the NRZ over other schemes. Only when using the NRZ DAC scheme, the quantization error of the CT $\Sigma\Delta$ modulator is input signal independent [12].

IV. CONCLUSION

In this paper, the impact of feedback DACs on the performance of CT incremental $\Sigma\Delta$ ADCs has been analyzed with an emphasis on biosensor applications. Different DAC schemes have been studied comparatively through theoretical

Fig. 5. PSD plots of the CT $\Sigma\Delta$ ADC employing different DAC schemes. $P_{sig} = -3.5$ dBFS, $f_{sig} \approx f_B/4$, and $N_{FFT} = 512$. $\tau_d = 10\%T_S$ for all DACs. (a) $SR_{NRZ} = 0.8 \times f_s$, $\sigma_{j,NRZ} = 0.1\%T_S$; (b) $SR_{HRZ} = 1 \times f_s$, $\sigma_{j,HRZ} = 0.02\%T_S$; (c) $SR_{RZ} = 1 \times f_s$, $\sigma_{j,RZ} = 0.04\%T_S$; (d) $SR_{SCR} = 6 \times f_s$, $\sigma_{j,SCR} = 0.1\%T_S$; (e) $SR_{SCSR} = 3 \times f_s$, $\sigma_{j,SCSR} = 0.4\%T_S$; and (f) $SR_{FSCR} = 2 \times f_s$, $\sigma_{j,FSCR} = 0.2\%T_S$.

analysis and behavioral simulations. The criteria for comparison are the immunity to timing errors and the influence on circuit requirements. In addition, by considering a typical test-case, the feedback DAC schemes have been further discussed, aiming to provide hints on achieving a power aware solution.

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