Two Novel Cascade $\Sigma\Delta$ Modulators for Broadband Low-Voltage A/D Conversion

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Abstract – This paper presents two new architectures of cascade $\Sigma\Delta$ modulators that, based on the use of resonance, increase their effective resolutions compared to previously reported topologies while presenting high robustness to non-linearities of the amplifiers and very relaxed output swing requirements. In addition, the use of loop filters based on Forward-Euler integrators, instead of Backward-Euler integrators as proposed in earlier approaches, simplifies the switched-capacitor implementation and makes the proposed architectures very suited for highly-linear broadband A/D conversion^{†1}.

I. INTRODUCTION

The increasing demand for high data-rate A/D converters for the next generation of telecom systems implemented in nanometer CMOS technologies is motivating the exploration of new topologies of wideband $\Sigma\Delta$ Modulators ($\Sigma\Delta$ Ms) [1]–[6]. Among others, the use of resonance [4] and/or unity Signal Transfer Function (STF) [2][3] are demonstrating to be good candidates for low-voltage implementation. On the one hand, loop-filter resonators allow to increase the effective resolution as compared with integrator-based noise-shaping filtering. On the other hand, by making STF unity, the integrators ideally process quantization error only, thus relaxing their requirements of amplifier gain non-linearity and output swing.

The above-mentioned strategies can be combined with cascade topologies in order to increase the order of the modulator whereas keeping stability and operating with low OverSampling Ratio (OSR) [5][6]. However, the implementation of in-loop resonators requires using Backward-Euler (BE) or non-delayed integrators which makes their Switched-Capacitor (SC) implementation more difficult.

This paper presents two novel topologies of cascade $\Sigma\Delta$ Ms intended for high-speed and low-voltage applications. Both modulators combine resonance techniques and unity STF. One of them is based on local resonance whereas the other one employs global resonance. In both cases, Forward-Euler (FE) instead of BE integrators are used, thus circumventing the implementation problems presented in the former architectures based on cascaded resonators.

The paper is organized as follows. Section II provides a background on previously reported resonance-based cascade $\Sigma\Delta$ M architectures, which make use of unity STF and resona-

tion. Section III describes the $\Sigma\Delta$ topologies proposed in this paper. Finally, behavioral simulations are shown in Section IV that demonstrate the benefits of the proposed architectures in terms of effective resolution and robustness to amplifier non-linearities and relaxed output swing requirements.

II. RESONATION-BASED CASCADE $\Sigma\Delta$ M TOPOLOGIES

An efficient way to increase the resolution without penalizing the number of integrators consists of including resonators inside the modulator loop filter. Thus, the so-called *local resonance* technique has been used in $\Sigma\Delta$ Ms considering either single-loop [4] or cascade topologies [5]. In both cases, this technique allows to shift the zeroes of the Noise Transfer Function (NTF) from DC, thus distributing them in an optimum way such that the in-band noise can be minimized [1].

In the case of cascade architectures, only the last stage normally uses resonance in order to reduce the complexity of the digital cancellation logic. As an illustration, Fig. 1 shows a cascade with local resonance in the last stage. This topology, originally presented in [5], takes advantage of both the unity STF of the first stage and the feedforward path at the last one, thus obtaining relaxed output swing requirements.

Recently, a new kind of resonance strategy, named *global resonance*, has been applied to cascade $\Sigma\Delta$ Ms [6]. This new approach, illustrated in Fig. 2 for a fourth-order cascade architecture, is obtained by feeding back the quantization error from the last stage to the previous one. Note that this topology achieves resonance thanks to a global path that feeds back a scaled version of the last stage quantization error at the input of the first stage quantizer.

Figure 1. Fourth-order cascade $\Sigma\Delta$ M architecture with local resonance and unity STF [5].

^{†1}. This work has been supported by the Spanish Ministry of Science and Education (with support from the European Regional Development Fund) under contract TEC2007-67247-C02-01/MIC, the Spanish Ministry of Industry, Tourism and commerce (FIT-330100-2006-134 SPIRIT) and the Andalusian Ministry of Innovation, Science and Enterprise under contract TIC-2532.

If a linear model is considered for the embedded quantizers, the $NTF(z)$ of the modulators in Fig. 1 and Fig. 2 is given by:

$$NTF(z) = \frac{-(1-z^{-1})^2 \cdot [1 - (2-K) \cdot z^{-1} + z^{-2}]}{d} \quad (1)$$

where d stands for the inter-stage gain. Note that the zeroes of $NTF(z)$ are a function of K , whose value can be optimally chosen to maximize the Signal-to-(Noise+Distortion) Ratio ($SNDR$). Indeed, practical cases may lead to a resolution increase of up to approximately 10dB [6].

Another conclusion that is derived from (1) is that increasing d (to reduce the quantization noise) yields a reduction of the feedback coefficient K/d (see Fig. 2). In practice, this results in a smaller capacitor ratio, which makes the electrical implementation more difficult and prone to circuit non-idealities.

III. PROPOSED CASCADE $\Sigma\Delta$ ARCHITECTURES

Previously reported resonance-based $\Sigma\Delta$ Ms like those shown in Fig. 1 and Fig. 2 require using BE or non-delayed integrators, $[H_{BE}(z) = 1/(1-z^{-1})]$, thus complicating the electrical implementation. Instead, the proposed architectures use both local and global resonance strategies and include loop filters based on FE integrators that are more suited for implementing SC A/D converters than previous reported topologies.

Figure 2. Fourth-order cascade $\Sigma\Delta$ M with global resonance [6].

A. Proposed cascade $\Sigma\Delta$ M with local resonance

Fig. 3 shows the proposed (I) fourth-order $\Sigma\Delta$ M architecture. This topology is a cascade architecture that implements local resonance with only FE or delayed integrators. The price to pay is that additional analog coefficients and a feedback path are needed. Note that this modulator is based on the one depicted in Fig. 1 with two modifications. The first one is the use of a second-order single-loop FE-integrator based resonator topology, proposed in [4], in the last stage of the cascade. On the other hand, the use of unity STF at the first stage allows feeding the second stage with only one branch [3][7].

B. Proposed cascade $\Sigma\Delta$ M with global resonance

Fig. 4 shows the second proposed topology, that makes use of unity STF at every stage whereas resonates through a feedback path from the last stage to the previous one, i.e. using global resonance.

However, as a consequence of using FE integrators, a scaled addition of the delayed last-stage quantization error is required at the input of the 1st-stage quantizer. Nevertheless, in order to overcome the implementation of the extra analog delay in Fig. 4—and an additional inter-stage Digital-to-Analog Converter (DAC), marked with $\otimes$ for clarity, that provides the last-stage quantization error to the first stage—a more efficient mode to

Figure 4. A first approach to the proposed (II) cascade with global resonance topology.

Figure 3. Proposed (I) cascade $\Sigma\Delta$ M with local resonator.

realize the global resonance with unity STFs stages is described below. Indeed, analysing the linearized Z-transform of Fig. 4, the delayed quantization error of the last stage can be directly obtained as

$$X_4(z) + I_2(z) = -z^{-1} \cdot E_2(z) \quad (2)$$

This modification results in the architecture depicted in Fig. 5. Note that, in addition to avoiding the use of both an extra analog delay and an inter-stage DAC, the $\Sigma\Delta\text{M}$ in Fig. 5 requires only one analog coefficient (K) to make the resonance, instead of the three coefficients [K , $(1 - K)$ and $(2 - K)$] in Fig. 3, which simplifies the electrical implementation and reduces the sensitivity to circuit non-idealities.

IV. SIMULATION RESULTS

In order to compare the performance of the proposed $\Sigma\Delta$ architectures (Fig. 3 and Fig. 5), several behavioral simulations has been done using SIMSIDES, a Simulink-based time-domain simulator for $\Sigma\Delta$ modulators [8]. All topologies operate with 4-bit internal quantizers, an inter-stage gain (d) of 1, a 1-V reference voltage and a very reduced oversampling ratio of 4. In addition, all the following simulations include kT/C noise sampled by 0.25-pF capacitors at the first integrator. Also, the embedded DACs are assumed to be linear.

As an illustration, Fig. 6 compares the effect of resonance on the output spectrum of the proposed topologies to that of a traditional 2-2 cascade (MASH), for a -6dB Full Scale (dBFS) input level. Note that, thanks to the resonance, a notch—clearly visible in Fig. 6a—is produced close to the bandwidth in the proposed topologies.

The rounded optimal feedback coefficient that causes the resonance in the topologies depicted in Fig. 3 and Fig. 5 is $K = 0.4$, resulting in a shift of two zeroes of the NTF from 0 to $0.8 \pm j \cdot 0.6$. Because of this optimum distribution of the NTF zeroes, the in-band noise is minimized. This is better illustrated in Fig. 7, where the $SNDR$ is represented versus the input amplitude. In this example the use of resonance increases the resolution of the proposed architectures by roughly 10.5dB within the whole input range compared to a traditional cascade.

Another advantage of the proposed architectures comes

from the use of unity STFs, yielding to the subsequent reduction of the amplifiers' output swing. This is illustrated in Fig. 8 by plotting the histograms of the integrator outputs in the architectures proposed in this work and those corresponding to Fig. 2. In addition, a classical cascade 2-2 architecture is also included in the comparison for the sake of completeness. Note that the output swing requirements of the proposed topologies —only 0.15V for the 1st and 3rd amplifiers; and 0.1V for the 2nd and 4th ones— are smaller than the ones for the modulator of Fig. 2 and for the traditional cascade. This is translated into a better linearity of the proposed architectures.

Figure 6. Modulator spectrum: (a) with and (b) without resonance.

Figure 5. Proposed (II) cascade $\Sigma\Delta\text{M}$ with global resonance.

Figure 7. SNDR versus input amplitude.

Figure 9. Effect of amplifier non-linearities on the SNDR (-6dBFS input level).

Figure 8. Output swing requirements for the amplifiers of: a) Traditional MASH, b) Global resonance structure in Fig. 2, and c) Proposed (I) and (II) modulators (-6dBFS input level).

The latter is illustrated in Fig. 9 by plotting the effect of amplifier gain non-linearity on the SNDR. In this simulation, a finite gain of 55dB is considered for all the amplifiers, while the gain second-order non-linearity of the first stage amplifiers is varied. Note that, compared with classical cascade architectures, the presented $\Sigma\Delta$ Ms have much better linearity performance.

CONCLUSIONS

Two novel topologies of cascade $\Sigma\Delta$ Ms have been presented. They combine a resonance-based loop filter with a unity STF to achieve very reduced output swing requirements for the amplifiers, whereas increasing the modulator resolution and its robustness with respect to non-linearities as compared to previous approaches. These characteristics make the proposed modulators very appropriate for the implementation of low-voltage wideband A/D conversion.

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