Sturdy MASH Δ-Σ modulator

N. Maghari, S. Kwon, G.C. Temes and U. Moon

A new Δ-Σ modulator is proposed. Its operation is similar to that of a multi-stage noise-shaping structure but requires no digital noise cancellation filters. Thus, the need for matching required between analogue and digital filters is eliminated. Simulation results and mathematical analysis demonstrate the effectiveness of this structure.

Introduction: With delta-sigma (Δ-Σ) modulators (DSMs) heading towards low-power high-speed applications with low oversampling ratio (OSR), the employing of higher-order noise shaping is necessary to achieve the desired signal-to-noise-and-distortion ratio (SNDR). The single-loop high-order DSM can provide the required SNDR with relaxed analogue circuit requirements, but is prone to loop instability. On the other hand, the multi-stage noise shaping (MASH) structure guarantees stable operation, but it requires high accuracy integrators to minimise the quantisation error leakage resulting from analogue–digital filter mismatches. These integrators are often implemented using power-hungry multi-stage operational amplifiers (opamps). The new, sturdy MASH (SMASH) structure presented in this Letter obviates the matching requirement, and thus allows using low-gain opamps for low-power high-speed operation.

MASH structure: As shown in Fig. 1, the MASH structure performs high-order noise shaping by feeding the error of the preceding stage to the next stage, which is usually realised by another Δ-Σ loop. In this Figure, L_{si} and L_{ni} denote the signal and noise loop filters of the ith stage. Digital filters H_i are used to cancel the first stage quantisation error. The overall output is given by

$$Y = STF_1X + (H_1NTF_1 - H_2STF_2)E_1 + H_2NTF_2E_2 \quad (1)$$

Here STF_i, NTF_i and E_i denote signal transfer function, noise transfer function and quantisation error of the ith stage, respectively. Hence, choosing the digital filters as $H_1 = STF_2$ and $H_2 = NTF_1$ will eliminate the first stage quantisation error, and the output will be

$$Y = STF_1X + NTF_1NTF_2E_2 \quad (2)$$

However, owing to circuit imperfections which cause mismatch between the analogue and digital filters, E_1 will appear at the output multiplied by STF_2NTF_{1a}–NTF_1STF_{2a}, where NTF_{1a} and STF_{2a} denote the actual analogue transfer function. This may limit the overall performance of the DSM [1].

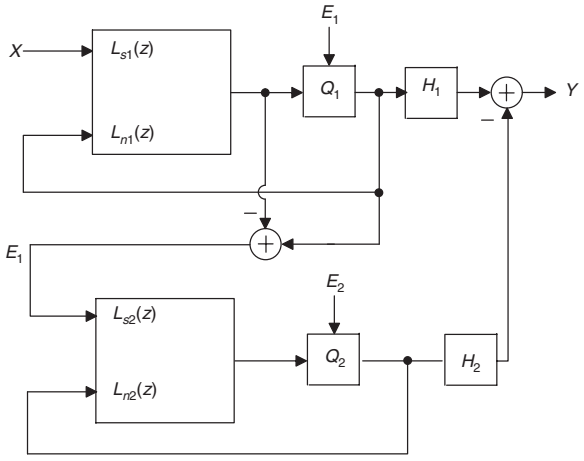

Fig. 1 *Block diagram of traditional MASH structure*

Proposed structure: Fig. 2 illustrates the block diagram of the proposed SMASH structure. The first stage quantisation error is fed to the second stage, as in traditional MASH structures, but the second stage output is directly subtracted from the output of the first stage quantiser in the digital domain. This technique not only allows removing the digital filters, but also provides additional noise shaping for E_1. The overall output is given by

$$Y = STF_1X + NTF_1(1 - STF_2)E_1 + NTF_1NTF_2E_2 \quad (3)$$

As can be seen from (3), E_2 is shaped by the product of the first and second stage *NTFs*, as in a traditional MASH structure; however, the first stage noise quantisation error is now shaped by the first stage NTF and also multiplied by $(1-STF_2)$. Proper choice for the second stage *STF* would result in additional noise shaping for E_1. For example, if the second stage *STF* is chosen to be a delay, i.e. $STF_2 = z^{-1}$, an extra first-order noise shaping is achieved. Another example is a 2 + 2 SMASH with fourth-order noise shaping for both E_1 and E_2, which can be realised by choosing the *STF* and *NTF* of the second stage as

$$STF_2 = 2z^{-1} - z^{-2} \quad \text{and} \quad NTF_2 = (1 - z^{-1})^2 \quad (4)$$

A possible implementation for this structure is shown in Fig. 3 where a modified structure of the SMASH architecture is presented. This operates by adding the second stage output to the input of the modulator, and subtracting it from the final output. This technique eliminates the need for a fast digital adder in the first stage [2].

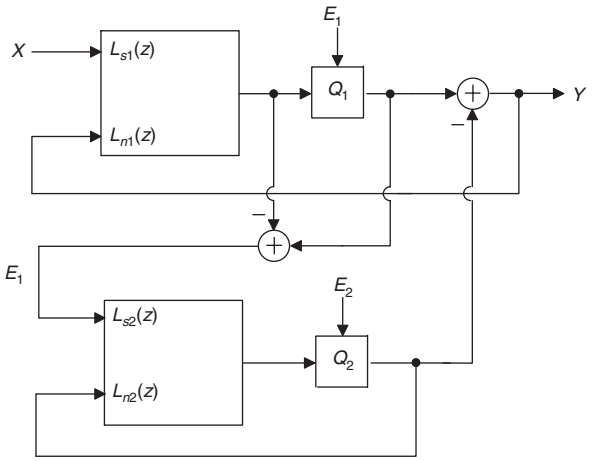

Fig. 2 *Block diagram of proposed SMASH structure*

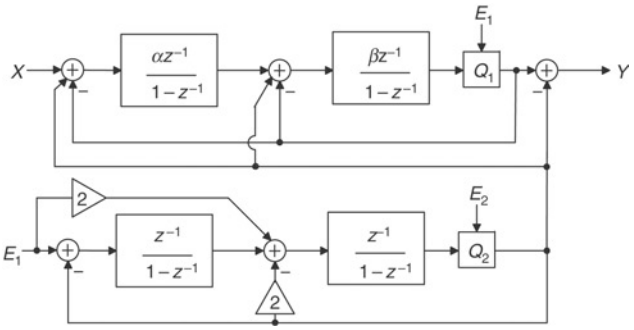

Fig. 3 *Proposed 2 + 2 SMASH structure*

As (3) shows, the SMASH structure is less sensitive to opamp gain and coefficient errors than the traditional MASH structure: finite opamp gain and coefficient mismatch will affect the zeros of the overall *NTF*, and the error will be suppressed by the second loop. This is because both *STF* and *NTF* are achieved by means of fully analogue components, in contrast with the traditional MASH structure in which digital filters form the overall noise transfer function. Employing fully analogue loop filters takes the advantage of the single loop high order DSM, and combines it with the stability of the multi-stage structure. This is because the injected quantisation noise from the second loop is uncorrelated with the signal in the first loop [3]. The contribution of the second stage output to the modulator input, shown in Fig. 3, should be highly accurate since any error at the modulator input deteriorates SNR. Hence, the second stage DAC needs to be highly linear. This can be alleviated by employing two separate DACs at the modulator input to reduce dynamic element matching complexity [2].

Simulation results: The proposed structure shown in Fig. 3, along with the traditional 2 + 2 MASH, was simulated using Simulink. Fig. 4 illustrates the SNDR against integrator opamp gain characteristics for the two structures. The assumed OSR was 16 for all simulations.

For both structures, 4-bit quantisers were used in each stage and −6 dB full-scale input signal was applied. Compared with traditional MASH, which requires an opamp gain of 60 dB for proper noise shaping, the proposed structure requires less than 30 dB opamp gain. Fig. 5 shows SNDR against input amplitude curves. For this simulation, an opamp DC gain of 50 dB was used. Owing to the direct feedback from the second stage output to the first stage input, the proposed SMASH structure saturates slightly earlier than the traditional one.

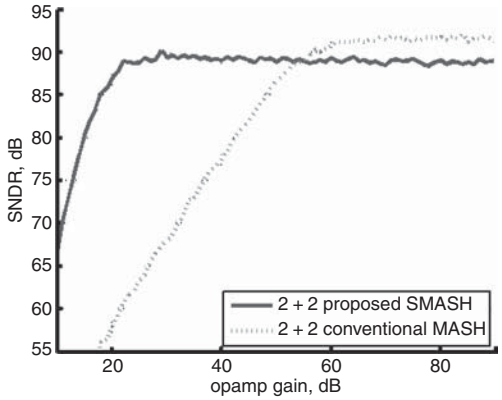

Fig. 4 *SNDR against opamp gain*

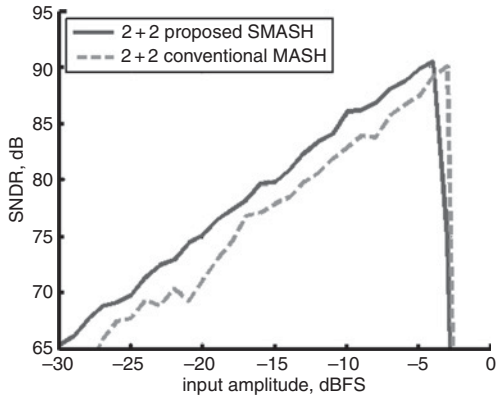

Fig. 5 *SNDR against input amplitude*

Conclusions: A new MASH structure has been proposed. Simulation results verify the effectiveness and robustness of this structure. Compared to the traditional MASH structure, which suffers from finite opamp gain and modulator coefficient variations, the proposed structure provides reduced sensitivity to circuit non-idealities. This makes the proposed structure suitable for low-power high-speed applications with relaxed analogue design requirements.

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