Simplified technique for syllabic companding in log-domain filters

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It is shown that when syllabic companding is applied to log-domain filters using dynamic biasing, their large signal linearity can be exploited to eliminate the state variable compensation circuit. Owing to its simplicity, the proposed technique has several advantages over previous approaches.

Introduction: Fig. 1*a* shows a first-order log-domain filter [1] which is ideally linear and time-invariant (LTI) [1, 2] between the large signal currents i_{1p} and i_{4p} in its input and output transistors (Fig. 1*a*, assuming $i_{1p} > 0$). i_{1p} is the sum of an AC input signal i_{in} and a bias I_{bias}. In traditional implementations, I_{bias} is a constant. The output i_{outp} is obtained by subtracting $(I_2/I_3)I_{bias}$ from i_{4p} as shown in Fig. 1*a* (I_2/I_3 is the DC gain of the filter [1, 2]).

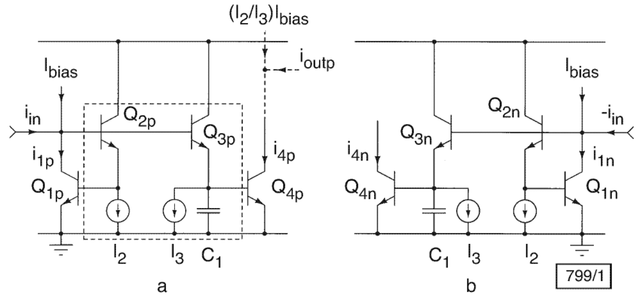

Fig. 1 *First-order log-domain filter and replica with same bias and opposite input*

a Filter
b Replica

In [3] dynamic biasing is applied to the circuit in Fig.1*a* by varying I_{bias} in accordance with the envelope of the input i_{in} so that I_{bias} is slightly larger than the minimum required value for i_{1p} to stay positive at all times. This lowers the power consumption and the output noise of the filter for small inputs and helps accommodate very large inputs. This also alters the 'gain' from the input current to the internal voltages and is analogous to syllabic companding [4, 5], but is much simpler to implement. However, due to time varying I_{bias}, i_{outp} is no longer just a filtered version of i_{in} and a state variable compensation circuit is required [3 – 6].

Proposed technique: If the single-ended filter shown in Fig. 1*a* is duplicated and operated with the same bias I_{bias} but an opposite input $-i_{in}$ as shown in Fig. 1*b*, the two output transistor currents i_{4p} and i_{4n} (Fig. 1) can be written as

$$\begin{aligned} i_{4p}(t) &= (i_{in}(t) + I_{bias}(t)) * h(t) \\ i_{4n}(t) &= (-i_{in}(t) + I_{bias}(t)) * h(t) \qquad (1) \end{aligned}$$

where $h(t)$ is the impulse response of the filter (between i_{1p} and i_{4p}, assumed ideal) and * denotes convolution. In the difference output $i_{out} = i_{4p} - i_{4n}$, the bias-dependent term $I_{bias}(t) * h(t)$ disappears. The relation between i_{out} and i_{in} is LTI and is the same as that between i_{outp} and i_{in} for the original log-domain filter (Fig. 1*a*) operating with a constant bias. In contrast with [3], no extra circuit is required for state variable compensation here. Deriving this result using the approach in [7] would require an internal description of a log-domain filter, and would be more involved. However, note that the above description applies, in addition to log-domain filters, also to other filters in which the input bias (current or voltage) controls the internal biasing.

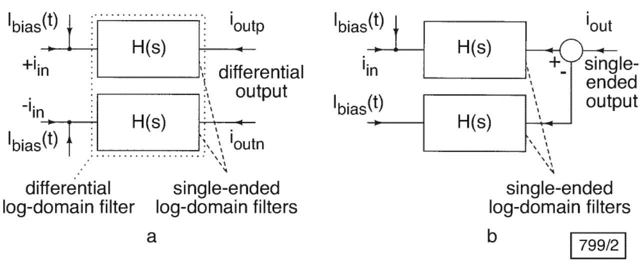

Fig. 2 *Distortionless dynamic biasing*

Any dynamically biased log-domain filter can be operated pseudo-differentially to cancel the effects of time varying bias as shown in Fig. 2*a*. Structures that operate on the differential input (e.g. the class-AB circuit in [1]) can also be used in Fig. 2*a* (dotted lines). In addition to the bias, even-order nonlinearities and common interferences are also cancelled by (pseudo) differential operation. If for some reason, e.g. interfacing, single-ended input and output are desired, the scheme shown in Fig. 2*b* in which the second filter is fed only the bias can be used.

Note that it is the LTI relation between the input and output currents in a log-domain filter that enables the cancellation of time-varying bias at the output. Pseudo-differential operation of a filter with time-varying gains at the input and output (classical syllabic companding) does not result in an LTI system [4, 6].

The base emitter voltage of Q_{1p} in Fig. 1 is given by $V_{be1p} = V_t \ln[(i_{in} + I_{bias})/I_s]$. An increase of i_{in} by a factor α causes I_{bias} to increase by the same factor since the latter is derived from the envelope of i_{in}. Therefore, V_{be1p} experiences only a DC shift $V_t \ln(\alpha)$. From linearity between i_1p and i_{4p}, it can be seen that the same is true of V_{be4p} as well. Thus, the AC signal applied to the (voltage mode) filter between the input and output transistors (enclosed by dashed lines in Fig. 1*a*) remains the same regardless of the input signal strength if dynamic biasing is used. This confirms the equivalence of dynamic biasing to syllabic companding. Like syllabic companding, dynamic biasing also increases the dynamic range of a log-domain filter.

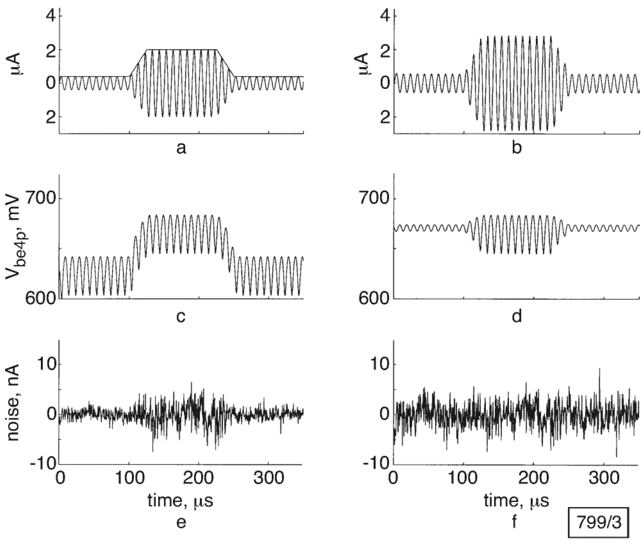

Fig. 3 *Simulation results*

a i_{in}, envelope *d* Constant bias
b Differential output *e* Dynamic bias
c Dynamic bias *f* Constant bias

Simulation results: The pseudo differential filter (using BJTs with $\beta_F = 50$, $V_{AF} = 10$V) in Fig. 1 with a –3dB frequency of 100kHz ($I_2 = I_3 = 1\mu$A, $C_1 = 61.5$pF) was simulated using HSPICE. The input is a sinewave with a changing envelope (Fig. 3*a*) at 100kHz. Substantial currents flow through the capacitor at this frequency and the circuit nonlinearities are sufficiently exercised. The circuit was simulated with (i) a dynamic bias, with the bias being 10% larger than the changing envelope, and (ii) a constant bias, with the bias being 10% larger than the largest envelope (= 2µA in Fig. 3*a*). The latter is the classical class-A operation. The two filters have exactly identical outputs (Fig. 3*b*). Figs. 3*c* and *d* show the base emitter voltage of Q_{4p} in the two cases. Syllabic companding, i.e. a constant internal voltage swing, is clearly seen in Fig. 3*c*. With a constant bias, the amplitude of the internal voltage varies with the input current (Fig. 3*d*). The results of HSPICE transient noise simulation (with uncorrelated noise current sources connected across each transistor) are shown in Figs. 3*e* and *f*. The noise reduction for small input signals due to dynamic biasing is evident. These results prove the external linearity and syllabic companding nature of the proposed dynamically biased filter.

Advantages of the proposed technique: The state variable compensation circuit used in [3] requires extra design effort, in some cases as much as for the main filter, and adds to the power consumption and noise of the filter. In the proposed technique (Fig. 2*a*), the signal-to-noise ratio

(SNR) is doubled (due to correlated signal and uncorrelated noise from the two halves) and so is the power consumption when compared to the simple log-domain filter. Halving all the capacitors and bias currents restores the original SNR and power consumption. Thus, as opposed to [3], no extra power consumption is required here for a given SNR and the power dissipated in the state variable compensation circuit is saved.

High dynamic range log-domain filters can also be realised using class-AB [1, 8] operation. Geometrically split [8] currents, the difference of which equals the desired input signal, are fed to a differential filter. The advantages of the proposed technique over class-AB instantaneous companding are: (i) the preprocessing circuit: the accuracy of the envelope detector is relatively unimportant as long its output is larger than the actual envelope, whereas the class-AB splitter has to accurately reproduce the input signal in its difference output to avoid added distortion; (ii) the envelope detector is simpler to design than a class-AB splitter, partly due to (i); (iii) mismatch leads to distortion because of internal nonlinearity in a class-AB filter and incomplete cancellation of bias components in a dynamically biased filter. However, slow varying bias components may be more acceptable than intermodulation distortion in many cases; (iv) the noise of the envelope detector cancels at the output of the filter, but the noise in the outputs of the class-AB splitter are in opposite phases for large signals and are not cancelled. This may degrade the SNR of the filter.

Conclusion: It has been shown that the design of syllabic companding log-domain filters can be greatly simplified by eliminating the state variable compensation circuit. The advantages of the proposed approach over previous methods for syllabic companding and also over instantaneous companding log-domain filters have been qualitatively discussed.

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