Performance Comparison of Continuous-Time IFLF and LF Low-Pass All-Pole OTA-C Filters

H. W. Su[*] and Y. Sun[**]

Department of Electronic, Communication and Electrical Engineering, Faculty of Engineering and Information Sciences, University of Hertfordshire, Hatfield, Herts, AL10 9AB, U.K.

[*]**Tel:** ++44 (0)1707 285082, **Email:** H.W.1.Su@herts.ac.uk
[**]**Tel:** ++44 (0)1707 284196, **Fax:** ++44 (0)1707 284199, **Email:** Y.Sun@herts.ac.uk

Abstract

This paper presents the performance comparison of two typical multiple loop feedback all-pole operational transconductance amplifier-capacitor (OTA-C) filters: Inverse-follow-the-leader-feedback (IFLF) and Leapfrog (LF) filters. Two fourth-order structures are analysed and compared in terms of sensitivity, maximum input signal, noise, and OTA nonideality effects on magnitude response. Simulation results obtained show that the LF structure is better than the IFLF structure in these four performances. The comparison is based on the realisation of the fourth-order Butterworth low-pass characteristic with 1MHz cut-off frequency.

I. Introduction

Multiple loop feedback (MLF) filters have started to draw attention from filter researchers and designers since the 1970's. Research has shown that MLF filters have lower passband magnitude sensitivity than cascade filters [1]. Also, such filters can realise functions with non-imaginary-axis zeros that ladder filters cannot achieve. However, these circuits are unsuitable for high frequency applications and fully integrated implementation since they are opamp-based and use resistors. OTA-C filters offer advantages over opamp-based filters in terms of design simplicity, high frequency capability, electronic tunability, monolithic integrability and reduced component count. Many OTA-C biquadratic filter structures offering variety of filtering characteristics have been generated, and their performances have been evaluated and compared. Recently a systematic method for structure generation and design of MLF OTA-C filters has been proposed, along with a number of interesting structures and easy-to-use design formulae [2-7]. The application of the proposed structures in computer hard disk drive systems was reported [8]. However, none of the reported literature has systematically investigated the performance comparisons of high-order MLF OTA-C filters in terms of sensitivity, maximum input signal, noise, and magnitude response. The aim of this paper is therefore to compare different MLF OTA-C filters in terms of the above performances. Our interest is in the most popular IFLF and LF filter structures.

The paper is laid out as follows; Section II presents the structures and design equations of the two filters. Analysis and comparison in terms of sensitivity, maximum input signal, noise, and magnitude response are given in Section III, IV, V, and VI respectively. The paper concludes with a brief summary in Section VII. Comparison results given in the paper should provide useful guides to filter designers in choosing the best structure in their filter design.

II. Fourth-Order IFLF and LF Structures

The canonical IFLF and LF OTA-C filter structures [6] are shown in Fig.1. With $\tau_j = C_j/g_{mj}$ denoting the time constant of integrator j, the transfer functions of the IFLF and LF structures can be derived as given in (1) and (2) respectively.

$$H(s) = \frac{1}{\tau_1\tau_2\tau_3\tau_4 s^4 + \tau_1\tau_2\tau_3 s^3 + \tau_1\tau_2 s^2 + \tau_1 s + 1} \tag{1}$$

$$H(s) = \frac{1}{\tau_1\tau_2\tau_3\tau_4 s^4 + \tau_1\tau_2\tau_3 s^3 + (\tau_1\tau_2 + \tau_1\tau_4 + \tau_3\tau_4)s^2 + (\tau_1 + \tau_3)s + 1} \tag{2}$$
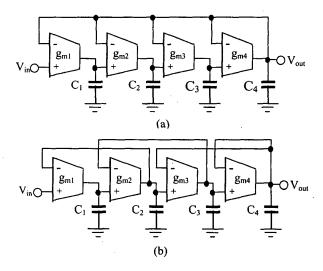

Fig.1. Canonical fourth-order (a) IFLF and (b) LF filter structures.

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The desired transfer function of the unity dc gain fourth-order all-pole low-pass filter is given by

$$H(s) = \frac{1}{B_4 s^4 + B_3 s^3 + B_2 s^2 + B_1 s + 1} \qquad (3)$$

Compare (1) and (2) with (3) gives the design formulae for the IFLF and LF filters given in (4) and (5) respectively.

$$\tau_1 = B_1, \quad \tau_2 = \frac{B_2}{B_1}, \quad \tau_3 = \frac{B_3}{B_2}, \quad \tau_4 = \frac{B_4}{B_3} \qquad (4)$$

$$\tau_1 = B_1 - \frac{B_3}{B}, \tau_2 = \frac{B}{B_1 - \frac{B_3}{B}}, \tau_3 = \frac{B_3}{B}, \tau_4 = \frac{B_4}{B_3}, B = B_2 - \frac{B_1 B_4}{B_3} \qquad (5)$$

The normalised fourth-order Butterworth low-pass filter characteristic is given by

$$H(s) = \frac{1}{s^4 + 2.61313 s^3 + 3.41421 s^2 + 2.61313 s + 1} \qquad (6)$$

When the filters realise the characteristic in (6), the values of τ_j for the IFLF and LF structures can be calculated using (4) and (5).

Note that both filter structures have the same number of differential OTAs and grounded capacitors. Thus, they have the same power consumption and chip area. But other performances will be different due to the difference in their feedback connections.

III. Sensitivity Analysis and Comparison

Sensitivity is one of the most important criteria in assessing the quality of filters. Thus, in the design of filters we need both to select low sensitivity realisations and reduce the sensitivities of the realisations we wish to use. This section compares the Schoeffler's multiparameter sensitivities of the fourth-order IFLF and LF filters.

The Schoeffler's multiparameter sensitivity is defined as [2]

$$SS = \sum_{i=1}^{4} \left| S_{\tau_i}^{H(j\omega)} \right|^2 \qquad (7)$$

where $S_{\tau_i}^{H(s)}$ are the sensitivities of transfer function H(s) with respect to integration constants τ_i. Based on (1-5), the sensitivity functions of the IFLF and LF filters can be obtained. When both filters realise the normalised fourth-order characteristic in (6), using (7) their Schoeffler's multiparameter sensitivities can be calculated and are shown against the normalised frequency in Fig.2. It is clearly observed that the LF structure has lower sensitivity than the IFLF in the whole frequency range. In particular, the peak sensitivity of the IFLF is about 1.64 times that of the LF at the normalised frequency of about 1rad/s.

The worst case (WS) sensitivities of the filters are also computed. Based on [2], the worst case sensitivity in this case is defined as

$$WS = \sum_{i=1}^{4} \left| S_{\tau_i}^{H(j\omega)} \right| \qquad (8)$$

The computed WS sensitivities agrees with the result obtained with the Schoeffler's multiparameter sensitivity
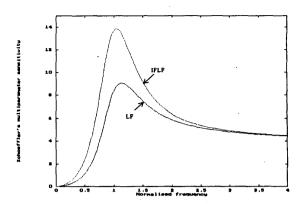

Fig.2. Comparison in terms of Schoeffler's sensitivity of fourth-order IFLF and LF filters.

comparison.

Thus, it is concluded that the LF filter is better than the IFLF filter in terms of sensitivity performance.

IV. Maximum Input Signal Analysis and Comparison

OTAs have the limited differential input voltage swing required to maintain an acceptable degree of linearity. The maximum input voltage of a filter is related to its dynamic range (DR) which is defined as the ratio of the maximum signal level at the input or output to the minimum signal or noise level at the same point. Thus, when the maximum signal of the filter is known, then the filter's DR can be determined. The DR of a filter, given the transfer function, is dependent on the DR of the filter network elements and the filter network architecture. And the limited DR of the OTA is confined by the linear input range and noise level which restrict the DR of the filter [9]. This section will find the maximum input voltages of the IFLF and LF filters.

First consider the fourth-order IFLF filter structure. The transfer functions from the filter input to the differential inputs of integrators are obtained as

$$\left. \begin{array}{l} H_1'(s) = 1 - H_4(s), \ H_2'(s) = H_1(s) - H_4(s), \\ H_3'(s) = H_2(s) - H_4(s), \ H_4'(s) = H_3(s) - H_4(s) \end{array} \right\} \qquad (9)$$

where $H_j'(s)$ is defined as

$$H_j'(s) = \frac{V_{dj}}{V_{in}}, \quad j = 1, 2, 3, 4 \qquad (10)$$

in which V_{dj} is the differential input voltage of the jth OTA and

$$H_j(s) = \frac{V_{oj}}{V_{in}}, j = 1, 2, 3, 4 \qquad (11)$$

in which V_{oj} is the output voltage of the jth integrator. So $H_j(s)$ is the transfer function from the filter input to the output of integrators. Using (4) and (9-11), the functions $H_j'(s)$ are obtained. We draw $\left| H_j'(j\omega) \right|$ and from these

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curves we can identify the their maximum values as $\left|H_1'(j\omega)\right|_{max} \approx 1.8$, $\left|H_2'(j\omega)\right|_{max} \approx 1$, $\left|H_3'(j\omega)\right|_{max} \approx 0.6$, and $\left|H_4'(j\omega)\right|_{max} \approx 0.29$.

The maximum input voltages of the IFLF and LF filters are determined by [5]

$$\left|V_{in}\right|_{max} = min\left\{\frac{V_{T1}}{\left|H_1'(j\omega)\right|_{max}}, \frac{V_{T2}}{\left|H_2'(j\omega)\right|_{max}}, \frac{V_{T3}}{\left|H_3'(j\omega)\right|_{max}}, \frac{V_{T4}}{\left|H_4'(j\omega)\right|_{max}}\right\} \quad (12)$$

where V_{Tj} is the maximum linear differential input voltage of the j OTA. Using (12), the maximum input voltage of the IFLF filter is determined as $0.56V_T$.

Now consider the fourth-order LF filter structure. The same set of transfer functions are obtained as

$$\left.\begin{array}{l} H_1'(s) = 1 - H_2(s), \ H_2'(s) = H_1(s) - H_3(s), \\ H_3'(s) = H_2(s) - H_4(s), \ H_4'(s) = H_3(s) - H_4(s) \end{array}\right\} \quad (13)$$

Similarly, the magnitudes of these functions are drawn and their maximum values are identified as $\left|H_1'(j\omega)\right|_{max} \approx 1.6$, $\left|H_2'(j\omega)\right|_{max} \approx 1.42$, $\left|H_3'(j\omega)\right|_{max} \approx 0.87$, and $\left|H_4'(j\omega)\right|_{max} \approx 0.29$. The maximum input voltage of the LF filter is determined as $0.63V_T$ from (12). Note that in the above we assume $V_{Tj} = V_T$ for both structures.

The results reveal that the LF filter allows higher maximum input signal voltage than the IFLF filter.

V. Noise Analysis and Comparison

Noise performance of active filters is of considerable interest to filter designers and researchers since both the dynamic range of an active filter and the effectiveness of signals recovery from a noise background using an active filter are dependent on the output noise of the filter itself [10]. The output noise level of an active filter depends on its system transfer function, the quality of the passive and active devices, the general impedance level of the filter, and the topology of the filter [10]. In continuous-time OTA-C filters, noise is contributed by all OTAs, and interfering signals are coupled into the circuit in various ways. We can normally treat the overall effect as equivalent to injecting noise sources only at the inputs of integrators. In practice, it is usually reasonable to assume that noise sources are uncorrelated with one another.

Assume that the input noise signals all have white power spectral density and equal to N_i^2. Then the total output noise power spectral density (PSD) of the IFLF and LF filters is given by [11]

$$PSD_{no}(\omega) = N_i^2 \sum_{k=1}^{4}\left|G_k(j\omega)\right|^2 \quad (14)$$

where $G_k(s)$ are the intermediate transfer functions from integrator inputs to the filter output. This section will find the output PSD functions of the fourth-order IFLF and LF structures.

From the definition of $G_k(s)$ given above, we can write

$$G_k(s) = \frac{V_{out}}{V_{ik}}, \quad k = 1, 2, 3, 4 \quad (15)$$

Using (14) and (15), we get the output PSD functions $PSD_{no}(\omega)/N_i^2$ which are shown in Fig.3. From the two curves, the output PSD of the IFLF configuration is lower than that of the LF for $0 < \omega \leq 0.4$rad/s, but thereafter the opposite situation occurs. In particular, the PSD of the IFLF structure is very much higher than that of the LF at $\omega = 1$rad/s and in the region close to this frequency. Thus, we conclude that the PSD performance of the LF filter is much better than the IFLF filter over wide frequency range.
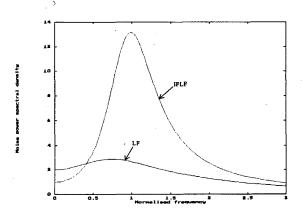

Fig.3. Comparison of noise performance of fourth-order IFLF and LF filters.

To further confirm the conclusion based on the PSD comparison, the output noise powers of the filters are computed using Simpson's 1/3 rule. The output noise powers ($0 \leq \omega \leq 3$) are computed as $P_{no}/N_i^2 = 22.53$dB and $P_{no}/N_i^2 = 14.63$dB for the IFLF and LF filters respectively.

VI. Analysis and Comparison of OTA Nonidelities Effects

The nonideal characteristic of OTAs will limit the performance of OTA-C filters. The nonideal model of the CMOS OTA includes the common-mode input capacitance C_{ic}, the differential-mode input capacitance C_{id}, the output capacitance C_o, the output conductance G_o, and the frequency dependent transconductance $G_m(s) = g_m /(1 + sT_p)$, where $T_p = 1/\omega_b$, ω_b is the bandwidth of the OTA [6].

For frequency performance simulation, the IFLF and LF filters realise the same Butterworth characteristic in (6) with the chosen cut-off frequency of 1MHz. The equal transconductance design is adopted with $g_m = 30.14\mu S$. Then using $C_j = g_m\tau_j$, the normalised capacitances are computed. Frequency denormalisation gives the nominal circuit capacitances in Table 1.

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Table 1. Nominal circuit capacitances for fourth-order IFLF and LF filters.

	C_1	C_2	C_3	C_4
IFLF	12.535pF	6.268pF	3.671pF	1.836pF
LF	7.343pF	7.566pF	5.192pF	1.836pF

Assume all OTAs have the same input impedance Z_{in}, output impedance Z_{out} and frequency dependent transconductance $G_m(s)$. Thus, we can assign $C_{icj} = C_{ic}$, $C_{idj} = C_{id}$, $G_{oj} = G_o$, $C_{oj} = C_o$ and $G_{mj}(s) = g_{mj}/(1 + sT_{pj}) = g_m/(1 + sT_p)$, $j = 1, 2, 3, 4$. The nonideal parameters in the macro-model of the CMOS OTA are assumed to be $C_{id} = 0.0385pF$, $C_{ic} = 0.0502pF$, $G_o = 113nS$, $C_o = 0.52pF$ and $T_p = 21.2ns$.

From Fig.4, the effects of OTA nonidealities on the frequency performance of the two filters are quite obvious. For the IFLF filter, it is noticed that the nonideal response has significant deviation from the ideal response especially at the cut-off frequency and stop-band. For the LF filter, the nonideal performance is observed quite close to the ideal one. Thus, the LF filter is better than the IFLF filter in terms of frequency performance.
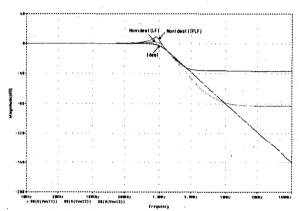

Fig.4. Simulated magnitude frequency responses of fourth-order IFLF and LF filters.

VII. Conclusions

Comparisons of sensitivity, maximum input signal, noise, and OTA nonideality effects of the IFLF and LF all-pole OTA-C filters have been presented for the fourth-order Butterworth low-pass characteristic with the cut-off frequency of 1MHz. It has been shown that the LF structure has lower Schoeffler's multiparameter and worst case sensitivities than those of the IFLF structure. In terms of maximum input signal voltage magnitude, the LF filter has a slight higher value (difference by $0.07V_T$) than that of the IFLF filter. Over wide frequency range, the noise of the LF filter is much lower than that of the IFLF filter. In terms of the effects of OTA nonidealities on frequency performance, it has been shown that the LF structure is

relatively less affected by these nonidealities than the IFLF structure. The overall conclusion is therefore that the LF structure is better than the IFLF structure.

Comparison simulations in the transistor level have confirmed the theoretical results. Clearly the results are suitable for balanced structure implementation of IFLF and LF filters [12], although they are obtained based on the single-ended structures.

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