PERFORMANCE COMPARISONS OF INTEGRATED FILTER REALISATIONS

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Introduction

In integrated filter design, the realisation of any given transfer function can be accomplished by a variety of different circuit structures. In switched capacitor (SC) technology, it is essential that the circuit be insensitive to parasitic capacitance. For this reason, the principal choices have been the cascade biquad and passive ladder simulation filters. Each circuit is characterised by different performance with respect to various design criteria. For example, it is well-known that ladder filters have low sensitivity to component deviations compared to biquads. However, they also appear to be unsuitable for realisation of certain transfer function categories where biquad structures have great superiority in both sensitivity and capacitance spread. Furthermore, recent developments in the design of ladder filters have provided the designer with several novel ladder structures which remain largely unexploited [1-3]. In the past, a comparison of the relative merits of different structures has been difficult due to the diverse nature of the design methods. However, recently matrix methods have considerably unified and regularised the design procedures for a wide range of filter types [3]. The PANDDA filter compiler has been developed around these techniques and has been applied successfully to many specialised integrated filter specifications [4]. In this paper, it is employed to produce a comprehensive survey of filter realisations over a range of transfer function classes and filtering problems. The properties of the filter structures are compared on the basis of sensitivity, dynamic range and total capacitance. The result of this investigation is a series of guidelines for the choice of a suitable filter structure according to the nature of the filter problem.

Performance measures

The following indices are used as global measures of system sensitivity $s(\omega)$ and dynamic range $d(\omega)$ respectively

$$s(\omega) = \left\{ \sum_i \left[\frac{c_i}{|H(\omega)|} \, \frac{\partial |H(\omega)|}{\partial c_i} \right]^2 \right\}^{1/2} \qquad (1)$$

$$d(\omega) = \left\{ \prod_m \left| H_m(j\omega) \right| \right\}^{1/M} \qquad (2)$$

where $\{c_i\}$ and $\{H_m\}$ are the sets of capacitances and opamp output voltage, respectively, and M is the number of opamps.

As the passband behaviour is of most interest to filter designers, two indices for system sensitivity and dynamic range, which are the average measures of $s(\omega)$ and $d(\omega)$ in the passband, are defined:

$$S = \frac{1}{\text{width of passband}} \int_{\text{passband}} s(\omega)\,d\omega \qquad (3)$$

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$$D = \frac{1}{\text{width of passband}} \int_{\text{passband}} d(\omega)\, d\omega \qquad (4)$$

Normally the chip area required for fabrication of a SC filter is measured by

$$T_C = \sum_{\text{all capacitors}} c_i \qquad (5)$$

but to reflect the influence of capacitance spread the following index will also be used

$$C = \left[\sum_{\text{all capacitors}} c_i^2 \right]^{1/2} \qquad (6)$$

An overall performance index of an SC filter can be defined as

$$P = \frac{C\ S}{D} \qquad (7)$$

For these indices, it is desirable to have lower S, T_C, C and P (the lower limit is 0). The maximum opamp output will always be assumed to have been scaled to 1, so that D will always be a positive number less than 1. It is desirable to have D close to 1, which means that all the opamps have equal output swing in the passband.

For a bandpass filter the relative bandwidth is defined to be

$$RBW = (\omega^+ - \omega^-)/\omega_m \qquad \omega_m = (\omega^+ \omega^-)^{1/2} \qquad (8)$$

where ω^+ and ω^- are the upper and lower edge frequency respectively. It is known that RBW has a great influence on the system performance.

Integrated filter structures

Two main rival filter architectures will be studied; cascade biquad and ladder simulations. Within each category there are a number of variants. Cascade biquads are composed of a succession of second order blocks. When used to realise transfer functions with imaginary axis zeros, these blocks can have either of two forms, characterised by the presence of E or F−type damping capacitors. The E−type block is known to be more efficient for the realisation of high−Q transfer functions than the F−type. There is a great degree of freedom concerning the ordering of the blocks and the pairing sequence of second order numerator and denominator transfer function terms. In PANDDA, an exhaustive trial is made over all possible combinations, finally selecting the one which has the minimum total capacitance.

Active ladder simulation filters may also take a number of possible forms. Matrix methods have revealed that the structure of the active filter depends on the type of matrix decomposition employed. Several families of ladder structures are now known, with the popular leapfrog and coupled−biquad filters occuring as special cases of a more general treatment [5,6]. The ones which will be studied here are:

1. Left−LUD
2. Left−direct (related to E−type coupled−biquad)
3. Right−LUD (related to leapfrog)
4. Right−Direct (related to F−type coupled−biquad)
5. UL−LU

Many forms of passive ladder prototype can be synthesised from a given transfer function according to the sequence of zero removals and type of two-port subnetwork. In PANDDA, all possible sequences are tested and the ladder simulation with the minimum total capacitance is chosen. This ensures that both biquad and ladder realisations compete fairly on the criterion of total capacitance.

Note that both cascade biquad and ladder structures have very similar numbers of components in realisation and so are entirely compatible from this respect. Unless stated otherwise, they are all one-opamp-per-pole (canonical) realisations and do not require sample-and-hold input stages.

Performance comparisons

Narrow bandpass filter design

A 6th order bandpass elliptic filter centred on 8kHz with passband ripple 0.1dB and stopband attenuation of 50dB is chosen as the basic form. Various SC realisations with sampling frequency of 200kHz are studied over a range of relative bandwidths (RBW). Plots of S, T_C, D and P are shown in Fig.1.

From Fig.1a it can be seen that the left-decomposition designs have very good total capacitance over the narrow band range but that the biquad method is better at around RBW=1. Regarding the sensitivity index S all the ladder designs are much better than the biquad method over the whole range as expected . The plots for cascade biquads are occasionally discountinuous . This is due to the fact that E-type and F-type biquads are selected according to Q-factor and discontinuity of internal nodal voltages may take place when the design is switched from E-type to F-type or vice versa affecting the dynamic range index. Another reason is that the pairing of biquadratic sections is carried out to achieve minimum total capacitance, which does not take into consideration voltage levels.

A comparison of the overall performance indices indicates that the left-LUD method is the best candidate for narrow band design RBW < 1 and the biquad method is best for bandpass design with RBW around 1. The sweep is repeated for 10th order filters and the performance index is shown in Fig.2. The similarity of these results to Fig.1d indicates that the conclusions apply across filter orders.

Wide bandpass filter design

From Fig.1 it is seen that both ladders and biquads are far from ideal for a very important area of filtering applications, that is, for the voice band application with passband from 300 Hz to 3400 Hz whose RBW > 3. For such wide band designs, the presence of lower band finite zeros is very detrimental to circuit performance. As the RBW increases these zeros approach the origin requiring extremely large capacitance spread for realisation. The deterioration process can be reduced if the lower band finite zeros are replaced at the origin (Fig.3). Since the zeros in the lower stopband are very close to origin anyway, this shifting will not affect the quality of the filter much.

A sweep of an eighth order design is done over a range of relative bandwidths (Fig. 4). This result echoes the conclusions for the previous specific example; that left-LUD design is still the best choice for this family of filtering applications, exceeding all others over the whole bandwidth range.

Lowpass filter design

A fifth order lowpass elliptic filter with passband ripple fixed to 0.1dB, passband edge of 1kHz is realised by various SC circuits with sampling frequency of 200kHz. The transition band ratio (passband edge/stopband edge) is varied from 1.01 to 10 and the change in quality index is plotted in Fig. 5.

Note that only the biquad cascade and right−LUD realisations are canonical with 5 opamps whereas the others have 6. It can be seen that the right−LUD is best overall. This is despite the better total capacitance of the biquad. The right−LUD has very good sensitivity and dynamic range properties. Left−LUD realisations are disadvantaged by a sensitivity peak at low frequency and by larger total capacitance.

Bandstop and highpass design

Bandpass and highpass filters are not often realised by SC ladder structures. This is due to a potential instability problem for filters with finite non−zero transmission at high frequency. However, there are a number of techniques to overcome these problems. A modulation method can be employed to easily convert a lowpass filter into a highpass one. The performance characteristics will still apply.

Bandstop filters can be realised by canonical ladder simulation methods [3] or by special circuits such as twintors. However, it appears that cascade biquads are superior in all respects for this type of filtering, having excellent sensitivity (even better than ladders) and very low total capacitance. The biquad seems to be ideally suited to notch transfer functions.

Allpass design

The filter structures in this paper can also be used to perform all−pass group delay qualisation. Recent design techniques for allpass ladder simulations have been presented. A comparison with the typical cascade biquad allpass circuit reveals that the ladder circuits have significant advantages in terms of total capacitance and amplitude sensitivity [3].

Conclusions

A summary of the conclusions follows;

1. Lowpass filters are best realised by right−LUD ladders
2. Left−LUD ladders have significant advantages for narrow and wide bandpass filters with (RBW << 1 or RBW >> 1)
3. Modest bandpass filters are best realised by biquads (RBW $\approx$ 1)
4. Biquads are superior to canonic ladder realisations of bandstop filters.
5. The performance of E−type coupled biquads is close to LUD and F−type is close to right−LUD structures.
6. UL−LU falls between left−LUD and right−LUD ladders in performance
7. Ladder all−pass realisations have better amplitude sensitivity than biquad

Acknowledgements

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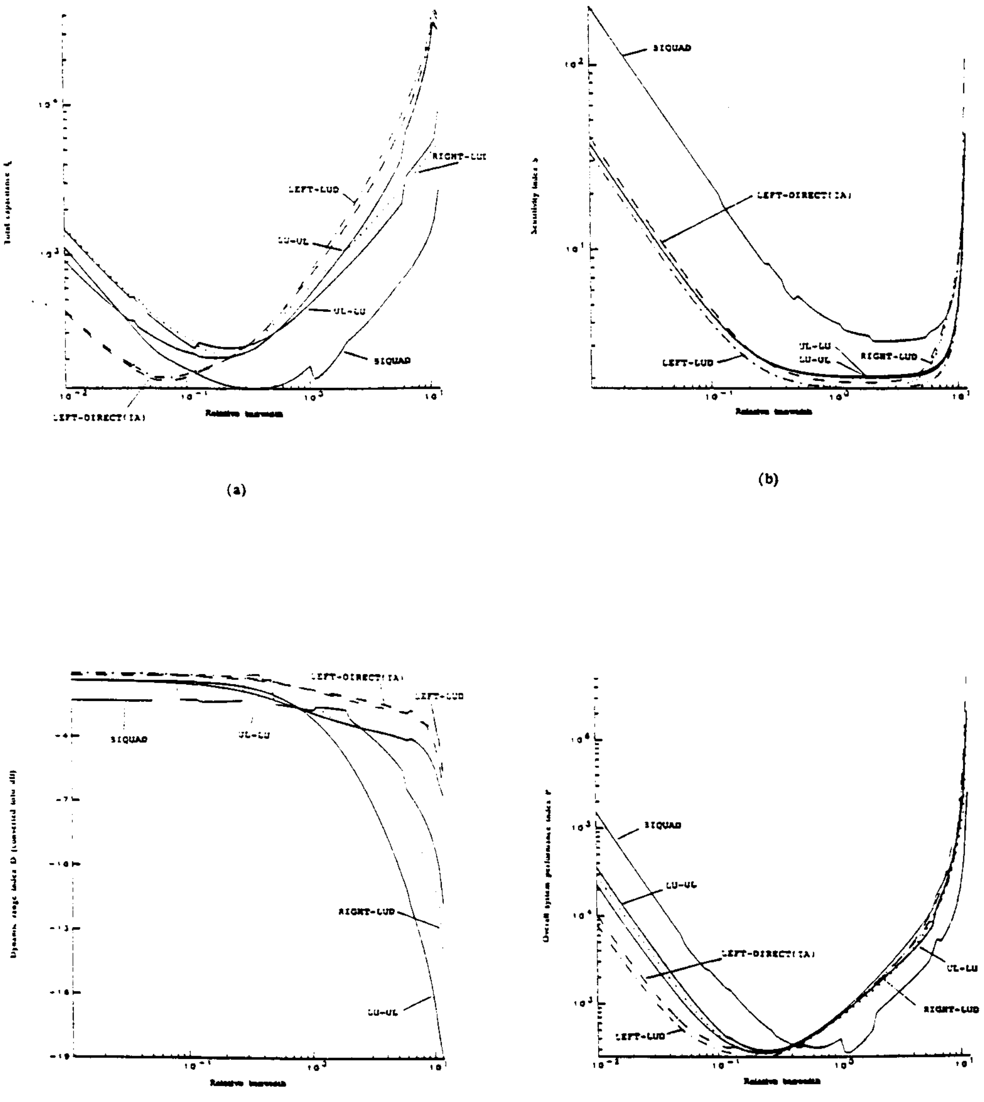

(a)

(b)

(c)

(d)

Fig. 1 Performance comparison for various sixth order bandpass filter realisations
(a) Total capacitance
(b) Dynamic range
(c) Sensitivity
(d) Performance index

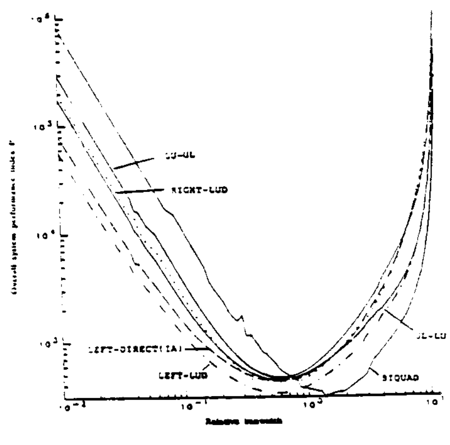

Fig. 2 Performance comparison for various tenth order bandpass filter realisations

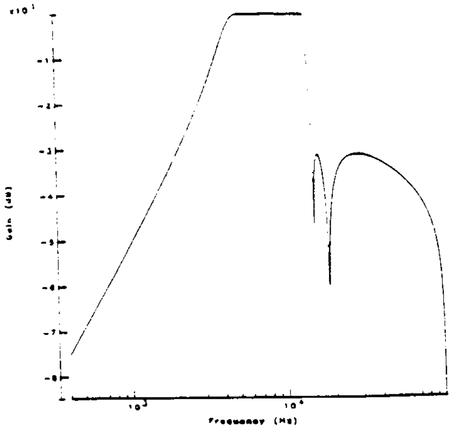

Fig. 3 Asymmetric bandpass filter with zeros shifted to origin

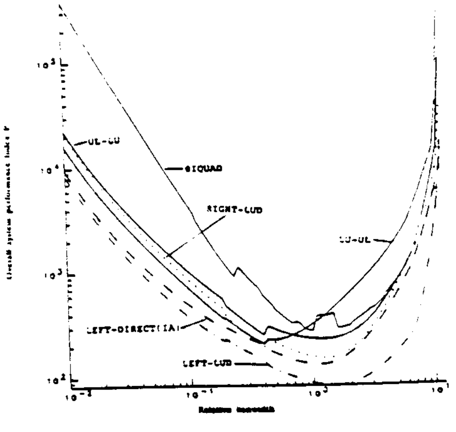

Fig. 4 Performance comparison of various eighth order asymmetric bandpass filters

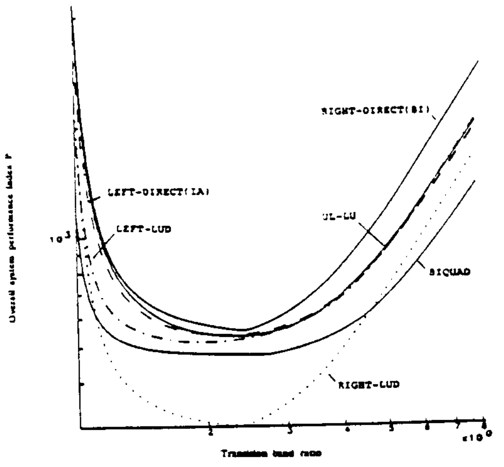

Fig. 5 Performance comparison for various fifth order lowpass filter realisations