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Active and passive sensitivity analysis for the second-order active RC filter families using operational amplifier: a review

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Abstract
This work is a review article that sheds light on the active and passive sensitivities of the active RC filters based on opamp. This work provides a detailed analysis through different filters realization criteria and sensitivity summary tables and quantitative insight by discussing the most significant. However, some are almost forgotten, filters families in the literature over decades. A detailed mathematical analysis for the passive sensitivity to compare the filters' realizations is presented. The concept of dealing between filter design theory and filter design circuit realization is highlighted. Some filters families are chosen from the literature for the analysis. Some detailed specifications tables for each filter family are given. Monte Carlo simulation is carried out on some filters to compare their passive sensitivity. Furthermore, the effect of the active sensitivity of some filters is verified through simulation by adjusting the input common-mode voltage to lower the DC gain of the amplifier. The results of the simulation match with the theoretical analysis and the summary provided in the specifications tables.

Keywords Analog filter · Active filter · Passive sensitivity · Active sensitivity · Bandwidth limitation

1 Introduction

Filters are essential blocks in communications and electronics systems applications. Ranging from large communication systems like radio-frequency (RF) transceiver systems [1], radar systems [2] and 5G systems [3], to on-chip communication systems like serial links and phase-locked loops (PLL), using filters to purify and adapt the processed signal in such systems is inevitable. At first, filters were realized using capacitors and inductors, known as passive RLC filters. However, the limitations of inductors' bulky size in low-frequency applications led to the idea of realizing inductorless filters [4]. Employing opamp to inductorless filters (i.e., activating the filter) has many advantages. One of the advantages of using opamp in the realization of filters is that it simplifies the idealization of the filter, and hence, the design procedure of the filter becomes systematic. It is also worth mentioning that those filters are suitable for discrete, hybrid thick-film and hybrid thin-film technologies. However, for integrated circuit (IC) technologies, other types of filters, namely, switched-capacitor filters, are designed instead [4]. Those filters consist only of capacitors and opamps [5]. The analysis of a second-order active RC filter depends mainly on some criteria. Starting with the filter's transfer function, some variables could be deducted to compare between different filter realizations. A pivotal concept to highlight is the difference between filter theoretical and circuit realization perspectives. A specific circuit realization can be tuned to obtain the desired filter response (i.e., the transfer function). For inductorless active filters, the complex poles are obtained from using feedback using only resistors and capacitors in addition to the operational amplifier [6]. Therefore, a set of specifications can be introduced to compare different filters for each perspective. Specifically talking, Cutoff frequency (ω_o), quality factor (Q), response selectivity, shaping factor, phase delay and, group delay are the specifications that could be checked to judge which

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theoretical filter transfer function mimics well the ideal filter response [7]. On the other hand, passive sensitivity, active sensitivity, the spread of elements, frequency limitation, circuit selectivity, number of passive elements and, number of active elements are most of the specifications to compare among different filter circuit realizations. Surveys in the literature aim to either introduce a new filter to enhance one of the criteria mentioned above or to focus and analyze some of them. For Example, in [8], the performance of around ten different filters was studied for over the effect of the limited gain-bandwidth product of the operational amplifier. A more practical insight was considered in [9] with simulation results and discussion for common realization issues. Many filters were categorized and analyzed mathematically in [6]. A detailed review on some of the well-known filters, specifically talking, KHN, and TT filters, was represented in [10]-[11] respectively. Table 1 concludes and compares this work with others in the literature that included any review to the second-order active filters. This work focuses on the specifications of the filters' circuit realization perspective and gives some detailed tables of these specifications. This work starts with some theoretical and mathematical relations for the second-order filters. Then, a survey for some of the filters families in the literature will be presented with the schematics and the direct transfer functions. This is followed by some tables that list some specifications of the presented filters. Finally, monte-carlo simulation results are presented to highlight the effect of the variations of the passive elements on the pole frequency for some of the filters.

2 Mathematical basics and criteria

As known for the second-order filters, the type of the filter could be controlled by the numerator of the transfer function, and the filter response of a type could be controlled by the denominator. Specifically talking, the cutoff frequency and the quality factor are the two main factors that judge the filter response to the signal frequency and the settling time. When comparing the realized transfer function to the required one, cutoff frequency and quality factor are expressed in the passive components of the filter eventually. This raises the importance of studying and reviewing the passive sensitivity effects on the filter response. The filter's ideal transfer function is derived as ideal opamps with infinite gain, which is not the actual case. Deriving the transfer function with the assumption of the finite opamp gain will result in a gain-dependent cutoff frequency and quality factor. This raises the importance to study the effect of the active sensitivity on the filter response. Some essential mathematical basics for such analyses are revised in this section. Equations 1–3 show the basic mathematical expressions for the filter transfer function.

$$T(s) = \frac{K_1 s^2 + K_2 s + K_3}{s^2 + \frac{\omega_o}{Q} s + \omega_o^2}, \tag{1}$$

where $s = j\omega$ and K_1, K_2 and K_3 are constant factors that decide the type of the filter. Equation 1 could be put on the form:

Table 1 Summary and Comparison of Filters Reviews from the literature

References	New filter presented	No. of reviewed filters	Criteria discussed/Summarized					Verification	
			$S^{\omega_o,Q}_{R_i,C_i}$	$S^{\omega_o,Q}_{A_o}$	$\frac{\frac{\Delta\omega_o}{\omega_o}, \frac{\Delta Q}{Q}}{\frac{\omega_o}{\omega_t}}$	No. of Rs,Cs	No. of amps	Sim	Exp
Hamilton72I [12]	✓	2	✓	✓	✓	✓	✓	–	✓
Hamilton72II [13]	✓	3	✓	✓	–	✓	✓	✓	✓
faulkner73 [8]	–	10	✓	–	✓	–	–	–	–
WBB74 [14]	✓	5	–	–	✓	–	–	–	✓
Soliman74 [15]	✓	1	✓	✓	✓	–	✓	–	–
MB75 [16]	✓	3	✓	✓	✓	–	✓	–	✓
Soliman76 [17]	✓	2	–	–	✓	✓	✓	–	–
Soliman78 [18]	✓	3	–	–	✓	✓	✓	–	✓
PMG80 [19]	✓	5	✓	✓	–	–	–	–	✓
Bowron80 [20]	–	4	–	–	–	–	–	–	–
BH81 [21]	✓	2	✓	✓	✓	–	–	–	–
KHN85 [22]	✓	3	✓	✓	✓	✓	✓	–	✓
KHN2008 [10]	✓	1	–	–	✓	–	–	✓	–
TT2008 [11]	–	1	–	–	✓	–	–	✓	–
ADI2009 [9]	–	8	–	–	–	–	–	✓	–
wai2009 [6]	–	17	✓	–	✓	–	–	–	–
This work	–	24	✓	✓	✓	✓	✓	✓	–

$$T(j\omega) = \frac{(K_3 - K_1\omega^2) + jK_2\omega}{(\omega_o^2 - \omega^2) + j\frac{\omega_o}{Q}\omega}. \tag{2}$$

The magnitude of the transfer function becomes:

$$|T(j\omega)| = \frac{\sqrt{(K_3 - K_1\omega^2)^2 + (K_2\omega)^2}}{\sqrt{(\omega_o^2 - \omega^2)^2 + (\frac{\omega_o}{Q}\omega)^2}}. \tag{3}$$

2.1 Sensitivity

There are two types of sensitivity: passive sensitivity and active sensitivity. It could be deduced from the definition of sensitivity that passive sensitivity measures the change of the cutoff frequency (ω_o) and the quality factor (Q) with the variations of the passive components (i.e., the resistances and capacitors). On the other hand, the active sensitivity measures that change with the opamp gain variations (i.e., the effect of the finite gain of the opamp to the filter response). The mathematical formula of sensitivity could be written as:

$$S_x^y = \frac{\partial y/\partial x}{y/x}, \tag{4}$$

where y is the factor that is affected , i.e., cutoff frequency and quality factor in this case, and, x is the impacting element, i.e., resistors, capacitors and, opamps in this case.

2.2 Spread of elements

This aspect measures how large or small the values of passive components spread to each other[4]. As the values of the passive elements depend on the geometry of the element, this spec was the target of many works as a figure-of-merit for the circuit performance [23]-[24].

2.3 Circuit selectivity

A filter's selectivity has different meanings in the literature depending on what perspective is adopted. Considering the theoretical perspective, selectivity would measure how a filter response represents the ideal filter response. This could be measured by calculating the slope of the transfer function magnitude frequency response curve at the 3-dB cutoff point (i.e., the half-power slope) [7]. Meanwhile, in-circuit realization perspective, selectivity is a measure for the maximum achievable range of the quality factor without affecting the cutoff frequency [i.e., independency of Q and ω_o] [15].

2.4 Effect of the roll-off of the gain of the operational amplifier (Bandwidth Limitation)

The effect of finite gain of the opamp is the active sensitivity analysis. Considering the bandwidth limitations, the operational amplifier's gain exhibits a low-pass response across frequency. To ensure a high gain and equality between the input pair voltages, the bandwidth of the opamp is the best frequency region for filtering operation. The high gain of the opamp in the bandwidth range ensures a perfect equalization between the positive and negative terminals, which is the ideal case for the filter response [4]. An excellent approximate method of calculating the bandwidth limitations is setting the gain of the opamp to its one-pole roll-off model and using Budak-Petrela analysis [15, 25].

The procedure of calculating the Budak-Petrela analysis for a given filter realization is as follows:

1) Derive the filter's transfer function assuming ideal infinite DC open-loop gain.
2) Exchange the DC gain of the amplifier in the transfer function with its first-order roll-off model [25] as in Table 2.
3) Derive the new characteristic equation of the filter with the which will be on the form [25]:

$$D(s) = P_1(s) + \frac{1}{\omega_t}P_2(s), \tag{5}$$

where ω_t is the gain-bandwidth product of the amplifier to the cutoff frequency of the filter, $P_1(s)$ is the nominal part of the characteristic equation and, $P_2(s)$ is the part resulting due to finite ω_t.
4) Calculate the fractional shift in the cutoff frequency and quality factor of the filter as follows [26]: Assuming the part of the new characteristic equation due to finite ω_t for the second-order filter is of the form:

$$P_2(s) = s(as^2 + b\omega_o s + c\omega_o^2), \tag{6}$$

where a, b and, c are constant coefficients and, ω_o is the cutoff frequency of the filter.

The fractional shift in the cutoff frequency will be calculated as follows:

$$\frac{\Delta\omega_o}{\omega_o} = -\frac{1}{2}(b - \frac{a}{Q})\frac{\omega_o}{\omega_t}. \tag{7}$$

Table 2 First-order Roll-off Models of Common Amplifiers

Type	First-order roll-off model
Operational amplifier	$\frac{V_o}{V_i} = \frac{-\omega_t}{s}$
Non-inverting amplifier	$\frac{V_o}{V_i} = \frac{(K+1)}{1+(K+1)\frac{s}{\omega_t}}$
Inverting amplifier	$\frac{V_o}{V_i} = \frac{-K}{1+(K+1)\frac{s}{\omega_t}}$

$K = \frac{R_b}{R_a}$

$\omega_t = A_o\omega_a$

ω_a is the open loop 3 dB bandwidth in radians per seconds

The fractional shift in the quality factor will be calculated as follows:

$$\frac{\Delta Q}{Q} = [(a-c)Q + \frac{1}{2}(b - \frac{a}{Q})]\frac{\omega_o}{\omega_t}. \tag{8}$$

2.5 Number of passive and active elements (i.e. Area and Power)

Comparing the number of passive components among different filter realizations of the same type gives an approximate estimation of the design area of each one and, had been utilized in the literature [27]-[18]. This may not be accurate 100% as two capacitors may still be smaller in area than one large capacitor. However, this is still a good comparison point under the same conditions and response as values of different capacitors and resistors would still be in the same range. Extending this concept to the active components (i.e., the opamp) directly gives a better comparison to the opamp power consumption as it is usually assumed that all opamps in the design are identical with high gain [4]-[28].

3 Second order active filters analysis

A *biquad* is an active RC circuit that represents a biquadratic transfer function. A biquad that uses one amplifier is called a single amplifier biquad (SAB) [29]-[30]. Other active filters use two op-amps to increase the quality factor [6]. Indeed, any configuration of capacitors with resistors can lead to countless resonators; therefore, this work aims to shed light on some forgotten filter families in the literature.

Table 3 SK transfer functions

Filter type	$T(s)$
Low-pass	$\frac{\frac{K}{R_1R_2C_1C_2}}{s^2+s(\frac{1}{R_1C_1}+\frac{1}{R_2C_1}+\frac{1-K}{R_2C_2})+\frac{1}{R_1R_2C_1C_2}}$
High-pass	$\frac{Ks^2}{s^2+s(\frac{1}{R_2C_1}+\frac{1}{R_2C_2}+\frac{1-K}{R_1C_1})+\frac{1}{R_1R_2C_1C_2}}$
Band-pass	$\frac{\frac{K}{R_1C_2}}{s^2+s(\frac{1}{R_1C_2}+\frac{1}{R_3C_1}+\frac{1}{R_3C_2}+\frac{1-K}{R_2C_2})+\frac{1+R_1/R_2}{R_1R_3C_1C_2}}$

3.1 Positive feedback Sallen-Key family

One of the oldest filters of all time is the Sallen-Key filter introduced in [31]. The filter was based on activating a second-order passive section with a non-inverting amplifier to obtain a higher achievable quality factor (Q) than the passive configuration. The transfer functions for the circuit realizations in Fig. 1 are listed in Table 3.

3.2 Decoupled-time-constant based filters

Decoupling of time constants of a filter is one of the most straightforward techniques to improve the performance [6]. The time constant decoupling means that each node of the filter corresponds to only one time constant i.e., connected to one resistor and one capacitor.. This should eliminate any cross-time constants from the transfer function [6]. Bach filter and Soderstrand filter families are presented next as an example of such filters.

3.2.1 Bach LPF

One of the oldest active low-pass filters was introduced by Bach in 1960 [32]. The main advantages of this filter, as stated in [33], were that it had minimum passive components (i.e., two capacitors and two resistors) and, it could be directly cascaded for a higher-order response without the need for compensation. Figure 2 shows the basic schematics for Bach's low pass filter. The limitations of the filters and possible solutions were studied in [33] with a proposed circuit modification. The transfer function is as follows:

$$T_{Bach}(s) = \frac{\left(\frac{1}{R_1R_2C_1C_2}\right)}{s^2 + \frac{s}{R_1C_1} + \frac{1}{R_1R_2C_1C_2}}. \tag{9}$$

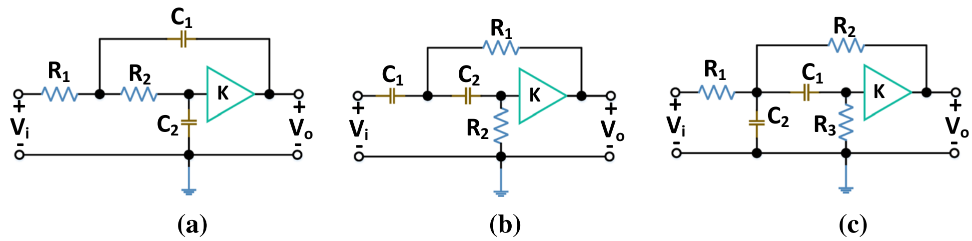


Fig. 1 Sallen-Key Filters Family: **a** LPF, **b** HPF, **c** BPF [31]

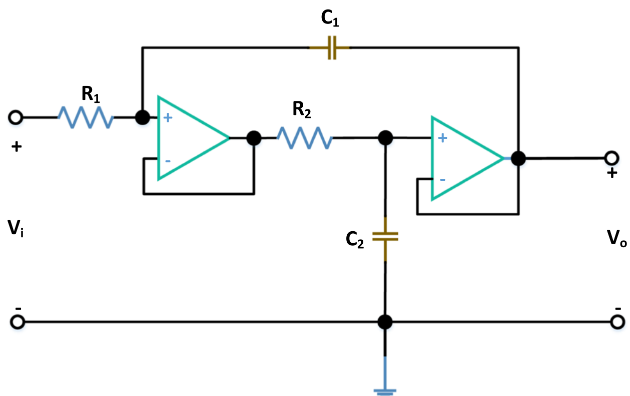


Fig. 2 Bach's LPF circuit schematics [32]

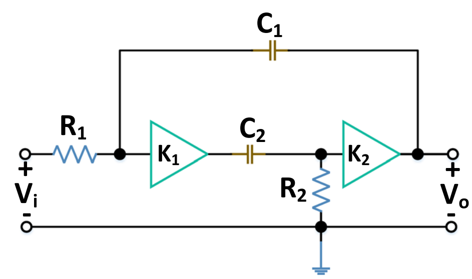


Fig. 3 Soderstrand-Mitra Filter Schematics [34]

3.2.2 Soderstrand-Mitra band-pass filter

The author in [34] had a brief description about the well-known developed active RC filters during that era and the challenges in their design. The author was interested in the fact that most of the former designs needed a very high amplifier gain to accomplish the low Q passive sensitivity. To deal with that problem, the author proposed a design that achieved a zero-sensitivity Q with reduced amplifier gain without affecting the active sensitivity. The proposed design was a modified version of Sallen-Key BPF with introduced additional amplifier in the forward path. Practical design recommended using one as inverting amplifier and one as a non-inverting amplifier is given by Eqn. 5 in [34] (i.e., $K_1 = -K_2$). The design schematics are shown in Fig. 3 and the transfer function is as follows.

$$T_{Sod}(s) = \frac{\left(\frac{K_1K_2}{1-K_1K_2}\right)\frac{s}{R_1C_1}}{s^2 + \frac{s}{(1-K_1K_2)}\left(\frac{1}{R_1C_1} + \frac{1}{R_2C_2}\right) + \left(\frac{1}{R_1R_2C_1C_2(1-K_1K_2)}\right)}. \tag{10}$$

3.3 GIC-derived biquads

The advantage of using a GIC in implementing an RC filter is that it has very low passive sensitivity [30]. Also, this type of building block could be used to realize a wide variety of functions [6].

3.3.1 Fliege filters family

A family of dual-amplifier building blocks based on generalized impedance converter (GIC) was discussed in [35]. Fliege also used the GIC concept to implement many functions, including elliptic and all-pass responses. Figure 4 shows Fliege family schematics for the four basic filters and, Table 4 shows the transfer functions.

3.3.2 Mikhael-Bhattacharyya (MB) filters family

The MB filter family was first proposed in 1975 as a universal building block that could be adjusted to achieve different responses [16]. Figure 5 shows the schematics of the four basic types of MB family and, Table 5 summarizes their transfer functions.

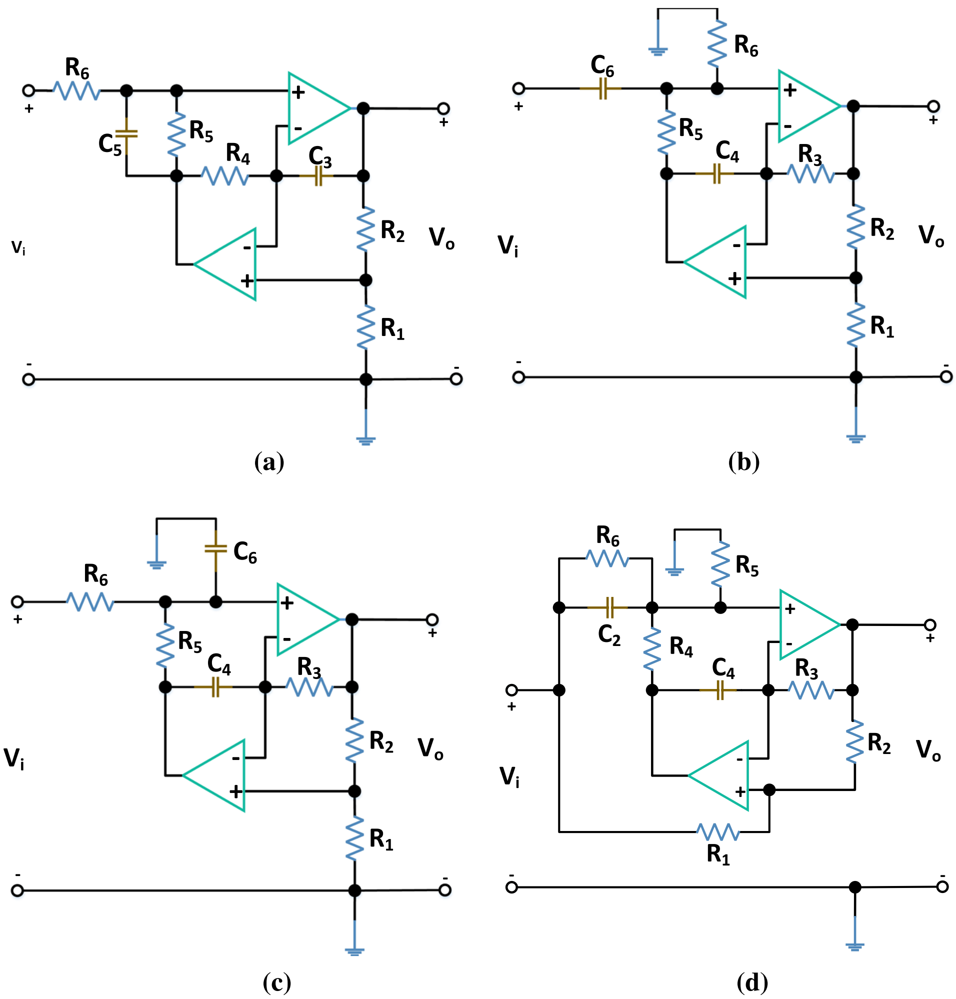


Fig. 4 Fliege Filters Family: **a** LPF, **b** HPF, **c** BPF, **d** NF [35]

Table 4 Fliege transfer functions

Filter type	$T(s)$
Low-pass	$\frac{\left(\frac{R_1+R_2}{R_2R_3R_5C_1C_2}\right)}{s^2+\frac{s}{R_4C_2}+\frac{R_1}{R_2R_3R_5C_1C_2}}$
High-pass	$\frac{s^2\left(1+\frac{R_2}{R_1}\right)}{s^2+\frac{s}{R_5C_2}+\frac{R_2}{R_1R_3R_4C_1C_2}}$
Band-pass	$\frac{\frac{s}{R_5C_2}\left(1+\frac{R_2}{R_1}\right)}{s^2+\frac{s}{R_5C_2}+\frac{R_2}{R_1R_3R_4C_1C_2}}$
Notch	$\frac{s^2+\frac{R_2}{R_1R_3R_4C_1C_2}}{s^2+\frac{s}{(R_5+R_6)C_2}+\frac{R_2}{R_1R_3R_4C_1C_2}}$

3.3.3 Padukone-Mulawka-Ghausi (PMG) filters family

In 1980, a universal filter building block was realized in [19]. A detailed comparison between the proposed design and other filter circuits was provided and well explained. Table 6 shows the transfer functions for PMG Family with the schematics shown in Fig. 6.

3.3.4 Bhattacharyya-Mikhael-Antoniou (BMA)

A family based on the generalized-immittance converters was proposed in [30]. This filter was introduced to get the unique feature of getting tuned through adjusting only the resistors. Also, cascading for obtaining higher-order filters did not provide any additional isolating amplifiers. Table 8 summarizes the presented 12 filters that could be achieved from the configuration of Fig. 7. All components are assumed to be normal resistors unless stated in the conditions.

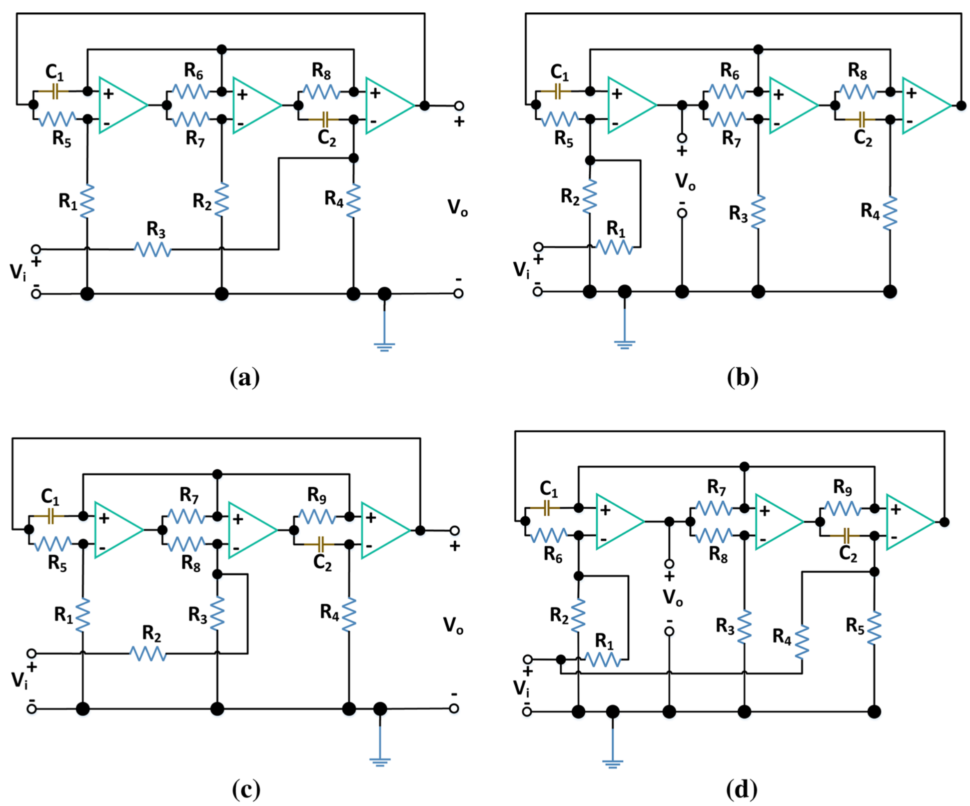


Fig. 5 Mikhael-Bhattacharyya Filters Family: **a** LPF, **b** HPF, **c** BPF, **d** NF [16]

Table 5 MB transfer functions

Filter type	$T(s)$
Low-pass	$\dfrac{(\frac{R_4(R_1+R_5)}{R_1(R_3+R_4)})(\frac{R_1(R_3+R_4)}{R_3R_4R_5R_8C_1C_2})}{s^2+s\frac{R_1R_7}{R_2R_5R_6C_1}+\frac{R_1(R_3+R_4)}{R_3R_4R_5R_8C_1C_2}}$
High-pass	$\dfrac{s^2\frac{R_2(R_3+R_7)}{R_3(R_1+R_2)}}{s^2+s\frac{R_1R_2R_7}{R_3R_5R_6(R_1+R_2)C_1}+\frac{R_1R_2}{R_4R_5R_8(R_1+R_2)C_1C_2}}$
Band-pass	$\dfrac{s\frac{R_7(R_1+R_5)}{R_2R_5R_6C_1}}{s^2+s\frac{R_1R_7(R_2+R_3)}{R_2R_3R_5R_6C_1}+\frac{R_1}{R_4R_5R_8C_1C_2}}$
Notch	$\dfrac{(\frac{R_2R_3R_8^2}{(R_1+R_2)(R_3+R_8)})(s^2+\frac{R_1}{R_4R_6R_9C_1C_2})}{s^2+s\frac{R_1R_2R_8}{R_3R_6R_7(R_1+R_2)C_1}+\frac{R_1R_2(R_4+R_5)}{R_4R_5R_6R_9(R_1+R_2)C_1C_2}}$

Table 6 PMG transfer functions

Filter type	$T(s)$
Low-pass	$\dfrac{\frac{R_2^2R_6^2(R_2+R_3)}{R_2R_3R_4R_5R_8C_1^2C_2^2}}{s^2+s\frac{R_2R_6(R_3+R_8)}{R_1R_3R_4R_8C_1}+\frac{R_6(R_7+R_8)}{R_4R_5R_7R_8C_1C_2}}$
High-pass	$\dfrac{s^2\frac{R_2^2R_6(R_2+R_3)C_3}{R_2R_3C_2(C_1+C_3)^2}}{s^2+s\frac{R_2R_6}{R_1R_3R_4(C_1+C_3)}+\frac{R_6}{R_4R_5R_7C_2(C_1+C_3)}}$
Band-pass	$\dfrac{s\frac{R_2^2R_6^2}{R_1R_4R_8C_1^2C_2}}{s^2+s\frac{R_2R_6(R_3+R_8)}{R_1R_3R_4R_8C_1}+\frac{R_6}{R_4R_5R_7C_1C_2}}$
Notch	$\dfrac{(\frac{R_2R_6(R_2+R_3)C_3}{R_3C_2(C_1+C_3)^2})(s^2+\frac{R_6}{R_4R_5R_8C_2C_3})}{s^2+s\frac{R_2R_6}{R_1R_3R_4(C_1+C_3)}+\frac{R_6(R_7+R_8)}{R_4R_5R_7R_8C_2(C_1+C_3)}}$

3.4 Multiple-feedback filters

Multiple-feedback is an old technique used to synthesize biquad filters with only one opamp (i.e., SAB). One great advantage of using multiple-feedback is that it provides highly stable realizations [6]. Deliyannis filter is one example of a SAB based on the multiple-feedback concept.

3.4.1 Deliyannis BPF

The Deliyannis band-pass filter was first discussed in 1968 in [36]. The transfer functions of the family are shown in Table 7 while basic schematics is introduced in Fig. 8 (Table 8).

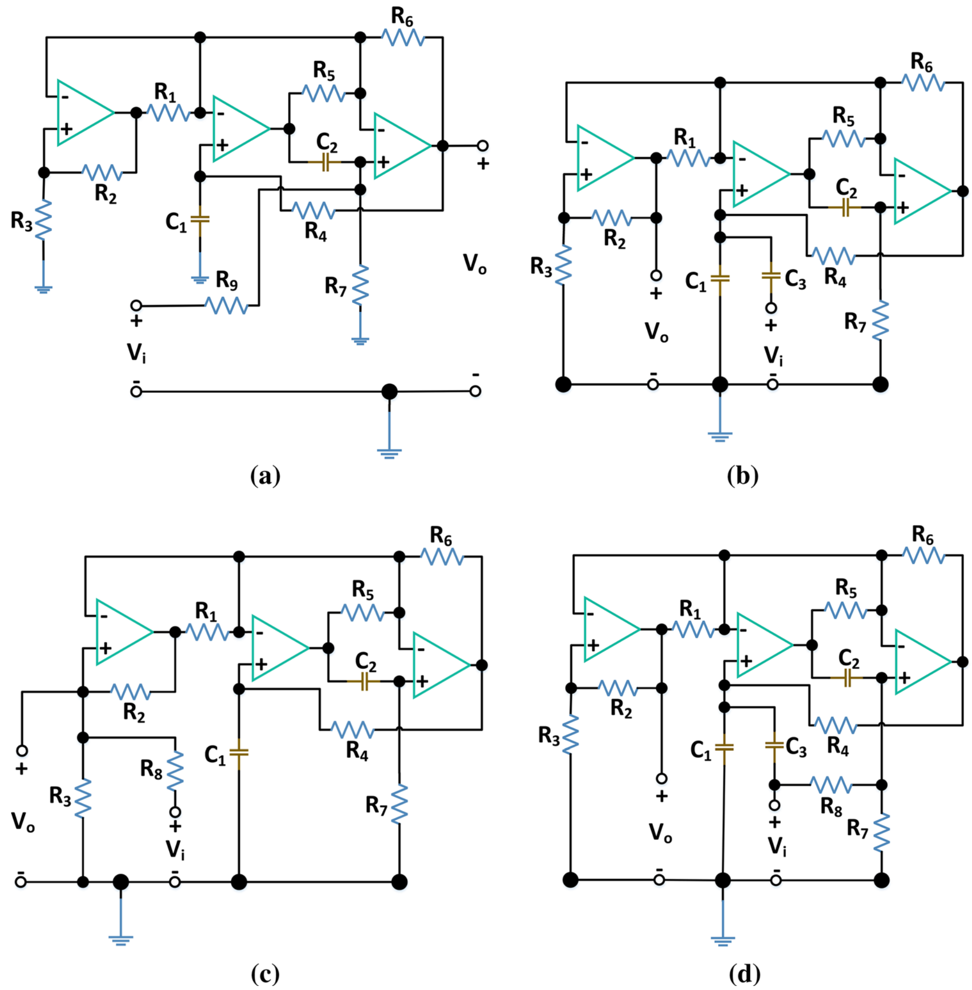


Fig. 6 Padukone-Mulawka-Ghausi Filters Family: **a** LPF, **b** HPF, **c** BPF, **d** NF [19]

Table 7 Deliyannis transfer functions

Filter type	$T(s)$
Band-pass I	$\dfrac{-\frac{s}{R_1C_2}}{s^2+s\frac{1}{R_2}(\frac{1}{C_1}+\frac{1}{C_2})+\frac{1}{R_2C_1C_2}(\frac{1}{R_1}+\frac{1}{R_3})}$
Band-pass II	$\dfrac{-s(1+K)\frac{1}{R_1C_2}}{s^2+s(\frac{C_1+C_2}{R_2C_1C_2}-\frac{K}{R_1C_2})+\frac{1}{R_1R_2C_1C_2}}$

$K = \frac{R_a}{R_b}$

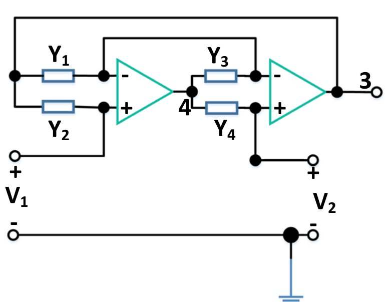


Fig. 7 BMA general building block [30]

3.5 State-variable-based filters

These filters are designed based on analog computer architecture [37] that are derived from the state-variable representation of continuous linear systems, which could be interpreted as using integrators to realize the filter. One crucial feature of those filters is that they can simultaneously realize low-pass, high-pass, and band-pass responses like KHN filter [6]. Also, it can be generalized to a global filter by adding an output amplifier to sum the three responses as mentioned above [6].

Table 8 BMA Family

Filter type	Conditions	$T(s)$
LPF I (Port 4)	$Y_2 = sC_2$ $Y_3 = sC_3 + G_3$ $Y_6 = Y_7 = 0$	$\frac{\frac{1}{R_1R_5C_2C_3}(1+\frac{R_8}{R_4})}{s^2+s\frac{1}{R_3C_3}+\frac{1}{R_1R_4R_5R_8C_2C_3}}$
LPF II (Port 3)	$Y_1 = sC_1$ $Y_4 = sC_4 + G_4$ $Y_8 = sC_8 + G_8$ $Y_5 = 0$	$\frac{\frac{1}{R_3R_7C_1C_4}(1+\frac{R_6}{R_2})}{s^2+s(\frac{1}{R_4C_4}+\frac{R_6C_8}{R_2R_3C_1C_4})+\frac{R_6(R_7+R_8)}{R_2R_3R_7R_8C_1C_4}}$
HPF I (Port 3)	$Y_3 = sC_3$ $Y_7 = sC_7$ $Y_8 = sC_8 + G_8$ $Y_5 = 0$	$\frac{s^2\frac{(1+\frac{R_2}{R_6})C_7}{C_7+C_8}}{s^2+s\frac{1}{R_8(C_7+C_8)}+\frac{R_2}{R_1R_4R_6C_3(C_7+C_8)}}$
HPF II (Port 3)	$Y_3 = sC_3$ $Y_7 = \frac{sC_7}{1+sC_7R_7}$ $Y_5 = Y_8 = 0$	$\frac{s^2(1+\frac{R_2}{R_6})}{s^2+s\frac{R_2R_7}{R_1R_4R_6C_3}+\frac{R_2}{R_1R_4R_6C_3C_7}}$
BPF I (Port 4)	$Y_2 = sC_2$ $Y_3 = sC_3$ $Y_5 = sC_5$ $Y_7 = 0$	$\frac{s\frac{C_5}{R_1C_2C_3}(1+\frac{R_8}{R_4})}{s^2+s\frac{R_8C_5}{R_1R_4C_2C_3}+\frac{R_8}{R_1R_4R_6C_2C_3}}$
BPF II (Port 3)	$Y_1 = sC_1$ $Y_7 = sC_7$ $Y_4 = sC_4 + G_4$ $Y_5 = 0$	$\frac{s\frac{R_6C_7}{R_2R_3C_1C_4}(1+\frac{R_2}{R_6})}{s^2+s(\frac{R_6C_7}{R_2R_3C_1C_4}+\frac{1}{R_4C_4})+\frac{R_6}{R_2R_3R_8C_1C_4}}$
BPF III (Port 3)	$Y_3 = sC_3$ $Y_8 = sC_8 + G_8$ $Y_5 = 0$	$\frac{s\frac{1}{R_7C_8}(1+\frac{R_2}{R_6})}{s^2+s\frac{R_7+R_8}{R_7R_8C_8}+\frac{R_2}{R_1R_4R_6C_3C_8}}$
NF I (Port 4)	$Y_1 = sC_1$ $Y_4 = sC_4$ $Y_8 = sC_8$ $Y_6 = 0$	$\frac{s^2\frac{C_4+C_8}{C_4}+\frac{R_5}{R_2R_3R_7C_1C_4}}{s^2+s\frac{R_5C_8}{R_2R_3C_1C_4}+\frac{R_5}{R_2R_3R_7C_1C_4}}$
NF II (Port 4)	• $Y_3 = sC_3$ $Y_7 = sC_7$ $Y_6 = 0$	$\frac{s^2+\frac{R_2(R_4+R_8)}{R_1R_4R_5R_8C_3C_7}}{s^2+s\frac{1}{R_8C_7}+\frac{R_2}{R_1R_4R_5C_3C_7}}$
NF III (Port 2)	• $Y_3 = sC_3$ $Y_7 = sC_7$ $Y_8 = sC_8 + G_8$	$\frac{s^2+\frac{R_2(C_7+C_8)}{R_1R_4R_5C_3C_7^2}}{s^2+s\frac{1}{R_8(C_7+C_8)}+\frac{R_2(R_5+R_6)}{R_1R_4R_5R_6(C_7+C_8)}}$

3.5.1 Kerwin-Huelsman-Newcomb (KHN) family

The KHN is one of the oldest and well-known filters family. The filter was introduced in [38], and it was extensively reviewed in [10]. The filter achieved low sensitivity with high achievable Q_p and slightly increased active sensitivity for $Q > 1000$. The schematics of the circuit realization is shown in Fig. 9 with the transfer functions of the filter listed in Table 9.

3.5.2 Tow-Thomas (TT) family

Another old and well-known filter family is the Tow-Thomas filter. The filter was first introduced by Tow in [39] and then by Thomas in [40]. The circuit was then extensively reviewed in [11]. The schematics of the circuit realization is shown in Fig. 10 with the transfer functions of the filter listed in Table 10.

3.5.3 Berka-Herpy family

The BH filter family is another universal building block family that was first proposed in 1981 in [21]. This filter was presented to target the minimum passive sensitivity criterion with a relatively low active sensitivity. The transfer function for this family is presented in Table 11 alongside the circuit realization in Fig. 11.

3.5.4 Akerberg-Mossberg family

The authors in [41] introduced four building blocks for realizing universal biquadratic function. In [42], the authors further studied one of the four blocks presented in the former paper and produced a modification to enhance the stability of the circuit. The modified circuit was also made to have independent cut-off frequency and quality factors, making it suitable for high-frequency applications. Also, it had the advantage of the quality factor independent of the opamp temperature variations. The synthesis of the four basic filter types transfers functions using that modified building block are summarized in Table 12 with the schematics in Fig. 12.

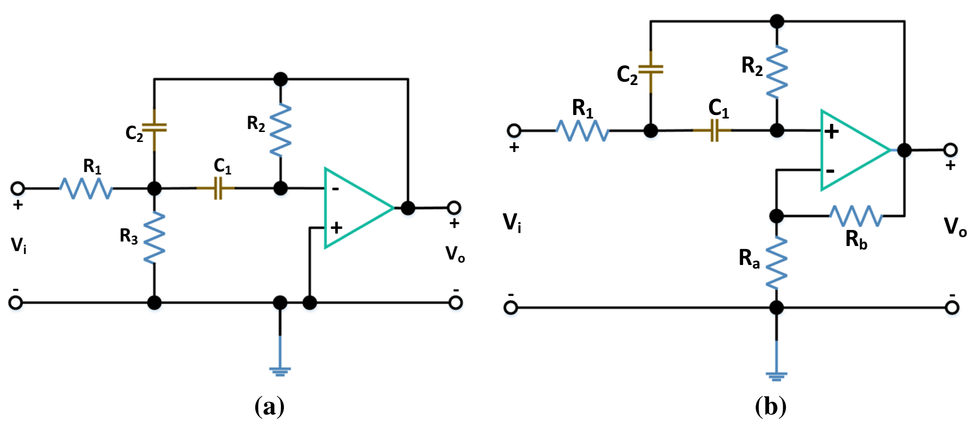


Fig. 8 Deliyannis Filters Family: **a** BPF I, **b** BPF II [36]

Table 9 KHN transfer functions

Filter type	$T(s)$
Low-pass ($\frac{V_3}{V_i}$)	$\frac{(\frac{2R_4}{R_3+R_4})(\frac{1}{R_1R_2C_1C_2})}{s^2+s(\frac{2R_3}{R_3+R_4})(\frac{1}{R_1C_1})+\frac{1}{R_1R_2C_1C_2}}$
High-pass ($\frac{V_1}{V_i}$)	$\frac{s^2(\frac{2R_4}{R_3+R_4})}{s^2+s(\frac{2R_3}{R_3+R_4})(\frac{1}{R_1C_1})+\frac{1}{R_1R_2C_1C_2}}$
Band-pass ($\frac{V_2}{V_i}$)	$\frac{s(\frac{2R_4}{R_3+R_4})(\frac{1}{R_1C_1})}{s^2+s(\frac{2R_3}{R_3+R_4})(\frac{1}{R_1C_1})+\frac{1}{R_1R_2C_1C_2}}$

Table 10 TT transfer functions

Filter type	$T(s)$
Low-pass ($\frac{V_2}{V_i}$)	$\frac{\frac{1}{R_2R_4C_1C_2}}{s^2+s(\frac{1}{R_1C_1})+\frac{1}{R_2R_3C_1C_2}}$
Band-pass ($\frac{V_1}{V_i}$)	$\frac{s(\frac{1}{R_4C_1})}{s^2+s(\frac{1}{R_1C_1})+\frac{1}{R_2R_3C_1C_2}}$
Low-pass ($\frac{V_3}{V_i}$)	$\frac{\frac{-1}{R_2R_4C_1C_2}}{s^2+s(\frac{1}{R_1C_1})+\frac{1}{R_2R_3C_1C_2}}$

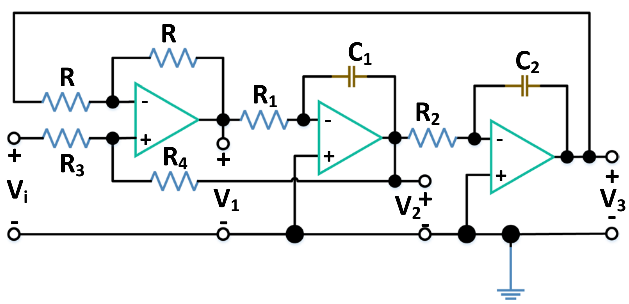


Fig. 9 KHN filter schematics [38]

Table 11 BH transfer functions

Filter type	$T(s)$
Low-pass	$\frac{\frac{R_6}{C_1C_2R_1R_2R_5}}{s^2+s\frac{1}{C_1R_3}+\frac{R_6}{C_1C_2R_1R_2R_5}}$
High-pass	$\frac{s^2}{s^2+s\frac{1}{C_1R_3}+\frac{R_6}{C_1C_2R_1R_2R_5}}$
Band-pass	$\frac{-s\frac{R_8(R_5+R_6)}{R_1R_5(R_7+R_8)C_1}}{s^2+s\frac{1}{C_1R_3}+\frac{R_6}{C_1C_2R_1R_2R_5}}$

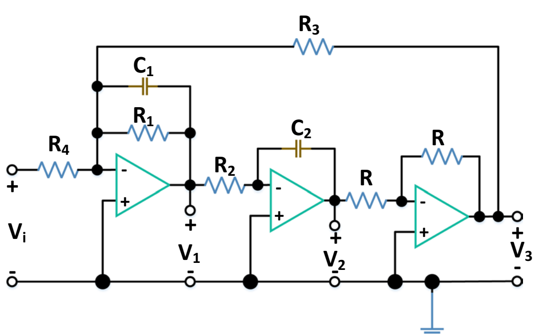


Fig. 10 TT filter schematics [39, 40]

3.6 Pole-zero cancellation based filters

3.6.1 Hamilton-Sedra 1972 (HS I)

In [13], the authors introduced this family which is shown in Fig. 13 with the transfer functions in Table 13 (Table 14). In that work, authors first demonstrated the dependency of sensitivities on the Q factor, which limits the maximum obtainable Q. Considering design approaches to take over this problem, the author mentioned two approaches which had been reported in [38, 43] and [44]. In brief, the first approach was the state variable approach that was used in designing the KHN filter, which uses at least three OAs for a second-order response. That paper discussed various second-order configurations based on the pole-zero cancellation technique. It also gave three designs, one with one amplifier for medium-Q and two with two amplifiers for high-Q. The third design could accomplish an all-pass filter with the advantage of saving one OA than the all-pass filter in [43]. Tables 13, 15 and, 16 show the transfer functions for the three approaches while Figs. 13, 14 and 15 show the basic schematics.

3.7 Rauch filters family

The Rauch filter section was introduced in [45]. In [8], the Rauch filter was mentioned alongside many other topologies to be compared for the effect of gain-bandwidth on the filter quality factor. Furthermore, the filter was utilized in [46] to

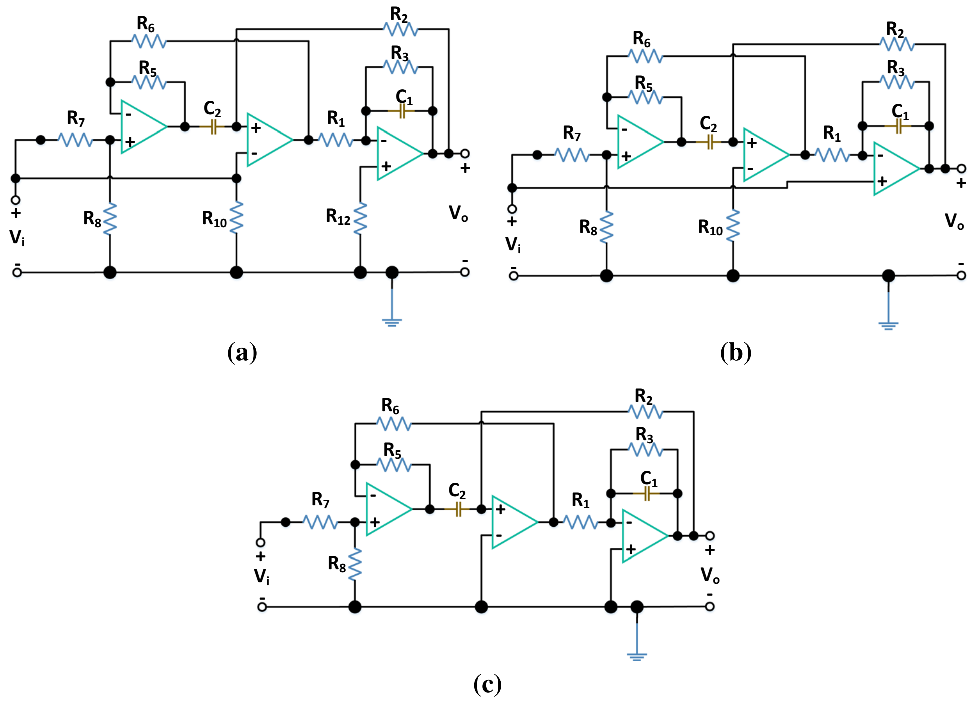


Fig. 11 Berka-Herpy Filters Family: **a** LPF, **b** HPF, **c** BPF [21]

increase the linearity of the low-pass filter section for an RF receiver system. The Transfer function of the Rauch filter is listed in Table 17 and the schematics are shown in Fig. 16.

3.8 Geffe filters family

In 1968, Geffe published a paper that presents some analysis on some well-known active RC filters [47]. First, the paper explained the Sallen-Key filter and how it encountered low passive sensitivity (1/6). However, the Sallen-key was limited to low-Q applications. The author explained a resonator design (Fig. 3 in [47]) where it has a low spread of passive elements and can achieve BPF of medium Q. Using the pole-zero cancellation technique for that circuit, A LPF could be obtained (Fig. 4 in [47]). The paper mentioned that dual-integrator feedback resonator is notably insensitive to amplifier parasitics: input impedance, output impedance, and roll off of the open-loop characteristic (phase compensation). The differential sensitivity of y to x is the fractional change in y due to the fractional change in x. The conditions stated in that work for the BPF emphasize $R_1 = R_2 = 1$, $C_1 = C_2 = \frac{1}{3Q}$, $R_3 = 9Q^2 - 1$ and $K = \infty$ with all values normalized and Q is the required pole quality factor. By using positive feedback, Geffe lowered the required gain at the expense of Q sensitivity [34]. The second design (Geffe II) gave a low-pass response and implied conditions of $R_3 = R_4$, $R_6 = R_5(\frac{Q-1}{Q+1})$, $C_1 = R_1/R_2$ and $C_2 = \frac{2Q}{R_3(Q+1)}$. The transfer functions of the Geffe family are shown in Table 17 and the schematics are in Fig. 17.

Table 12 AM transfer functions

Filter type	$T(s)$
Low-pass	$\frac{\frac{-R_3}{C_1 C_2 R_1 R_2 R_5}}{s^2+s\frac{1}{R_6 C_2}+\frac{R_3}{R_2 R_4 R_5 C_1 C_2}}$
High-pass	$\frac{-\frac{C_3}{C_2}s^2}{s^2+s\frac{1}{R_6 C_2}+\frac{R_3}{R_2 R_4 R_5 C_1 C_2}}$
Band-pass	$\frac{s(\frac{R_3}{R_5 R_8}-\frac{1}{R_7})\frac{1}{C_2}}{s^2+s\frac{1}{R_6 C_2}+\frac{R_3}{R_2 R_4 R_5 C_1 C_2}}$
Notch	$\frac{-\frac{C_3}{C_2}(s^2+\frac{R_3}{R_1 R_2 R_5 C_1 C_3})}{s^2+s\frac{1}{R_6 C_2}+\frac{R_3}{R_2 R_4 R_5 C_1 C_2}}$

3.9 All-pass based

This type is based on first-order all-pass sections like Tarmy-Ghausi filter [6].

3.9.1 Tarmy-Ghausi filter

Tarmy-Ghausi filter was proposed in 1970 in [48] to realize a stable high Q active RC filter. The realized Q was in the range of 1000 5000. The key feature of that work is that its Q is independent of the amplifier bandwidth and, it has low sensitivity compared to KHN filter. The design design schematics is shown in Fig. 18 and the transfer function is listed in 17 where $T_1 = R_1 C_1$ and, $T_2 = R_2 C_2$. The conditions required for high Q i.e., $Q_p \gtrsim 100$ are $T_1 = T_2 = T = 1$ and, $K_2 K_3 K_4 < 1$.

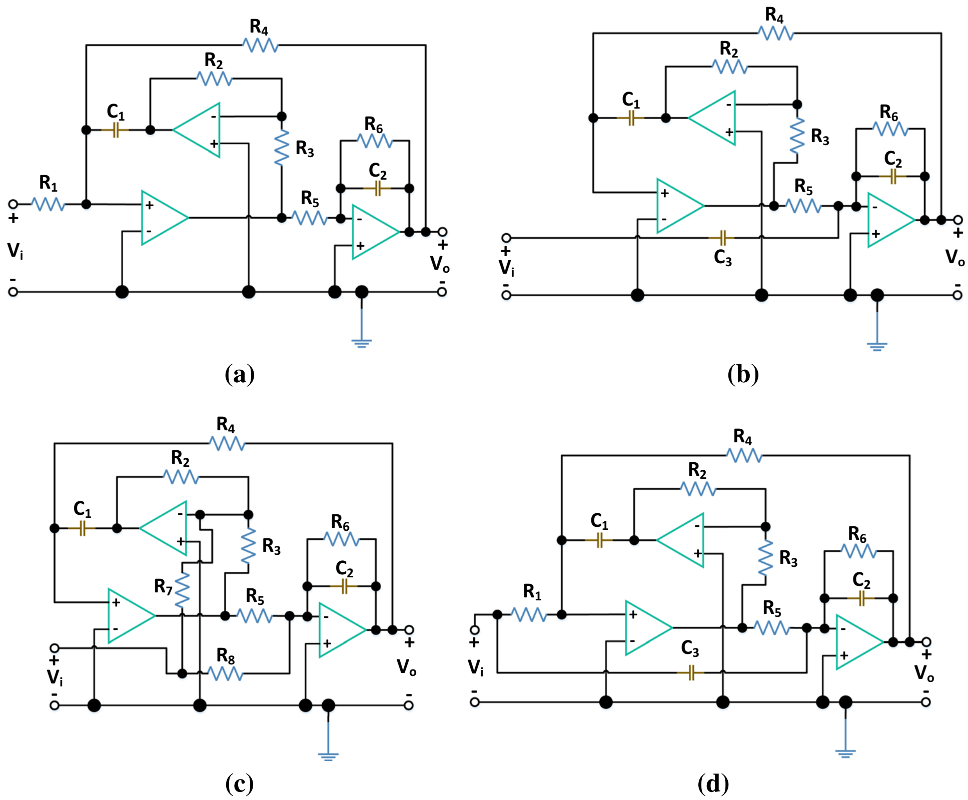


Fig. 12 Akerberg-Mossberg Filters Family: **a** LPF, **b** HPF, **c** BPF, **d** NF [42]

Table 13 Hamilton-Sedra72 IA transfer functions

Filter type	$T(s)$
Low-pass	$\frac{\frac{1}{R_1 R_2 C}}{s^2+s\frac{2}{R_Q C}+\frac{(1+2R/R_Q)}{R^2 C^2}}$
High-pass	$\frac{s^2}{s^2+s\frac{2}{R_Q C}+\frac{(1+2R/R_Q)}{R^2 C^2}}$
Band-pass	$\frac{\frac{s}{R_1 C}}{s^2+s\frac{2}{R_Q C}+\frac{(1+2R/R_Q)}{R^2 C^2}}$

Table 14 HS72 IA family conditions

Filter type	Condition
Low-pass	$R_1 = \frac{(2+a)+\sqrt{(2+a)^2-2(1+2a)T^2}}{2c(1+2a)}$ $R_2 = \frac{8+4a(2+a)+\sqrt{(2+a)^2-2(1+2a)T^2}}{2c(1+2a)}$
High-pass	$R_1 = \frac{(2+a)+\sqrt{(2+a)^2-2(1+2a)T^2}}{2c(1+2a)}$ $R_2 = \frac{8+4a(2+a)+\sqrt{(2+a)^2-2(1+2a)T^2}}{2c(1+2a)}$
Band-pass	$R_1 = \frac{(2+a)+\sqrt{(2+a)^2-2(1+2a)T^2}}{2c(1+2a)}$ $R_2 = \frac{8+4a(2+a)+\sqrt{(2+a)^2-2(1+2a)T^2}}{2c(1+2a)}$

3.10 Soliman filters

3.10.1 Soliman72 filter

An active notch filter was proposed in [49] by activating the twin-T network for achieving medium quality factor. It also has the advantage of having low passive sensitivity. However, it consists of 8 passive elements. The filter schematics are shown in Fig. 19 with the transfer function as follows:

$$T_{Sol72}(s) = \frac{s^2 + (\frac{1}{R_3 C})^2}{s^2 + s(\frac{4}{KR_3 C}) + (\frac{1}{R_3 C})^2}. \tag{11}$$

3.10.2 Soliman73 family

The author in [50] presented two different realizations for the second-order nonminimum phase transfer function. The

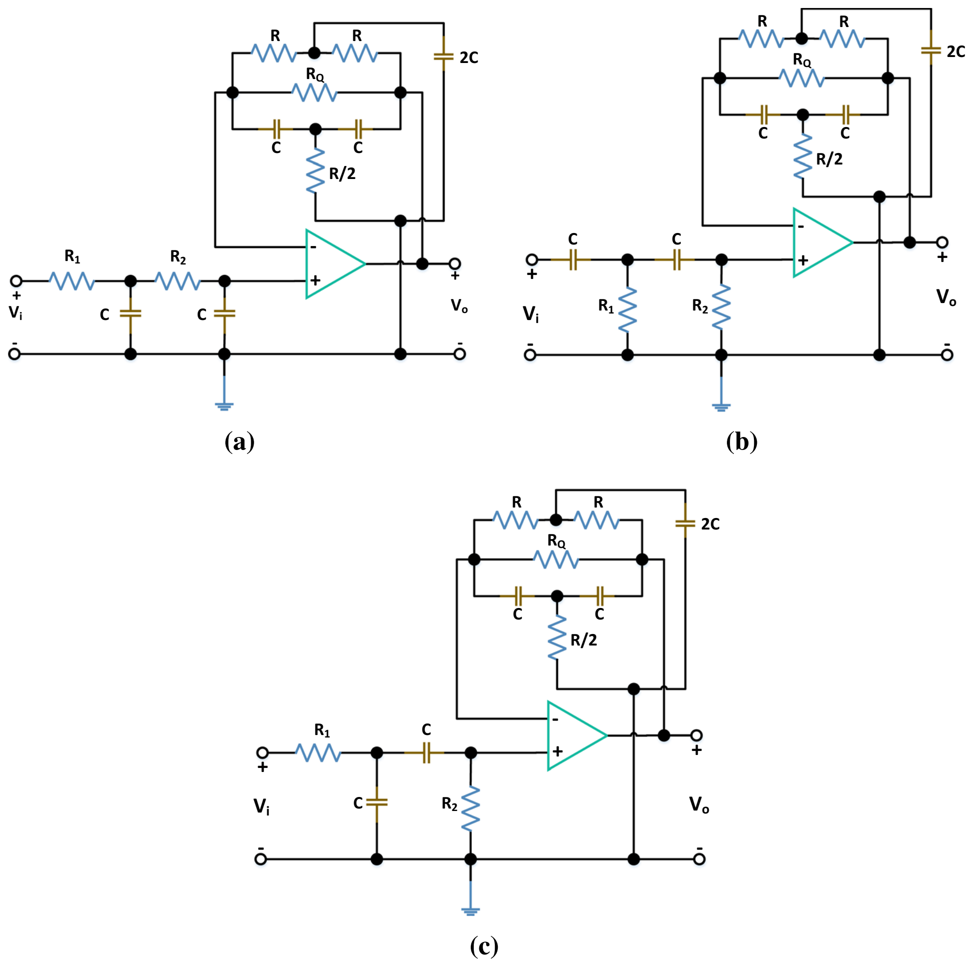


Fig. 13 Hamilton-Sedra72 IA Filters Family: **a** LPF, **b** HPF, **c** BPF [13]

first one has the advantage of being a SAB and, permanently stable while the second provides a unity gain factor, but it uses two opamps. The filter schematics are shown in Fig. 20 with the transfer function in Table 18 where the parameter a is dependent on the required quality factor.

3.10.3 Soliman74 family

In [15], an active second-order low-pass filter was presented with a unique feature of ω_o being insensitive to the gain-bandwidth product of the OA. The filter schematics are shown in Fig. 21 with the transfer function as follows:

$$T_{Sol74}(s) = \frac{\frac{(R_a+R_b)(R_c+R_d)}{R_aR_cR_1R_2C_1C_2}}{s^2 + s(\frac{1}{R_1C_1} + \frac{1}{R_2C_2} + \frac{1}{R_2C_1}) + \frac{R_aR_c+R_b(R_c+R_d)}{R_aR_cR_1R_2C_1C_2}}. \tag{12}$$

Table 15 Hamilton-Sedra72 IB transfer functions

Filter type	$T(s)$
Low-pass	$\frac{\frac{1}{R_1R_2C}}{s^2+s\frac{2}{R_QC}+\frac{(1+2R/R_Q)}{R^2C^2}}$
High-pass	$\frac{s^2}{s^2+s\frac{2}{R_QC}+\frac{(1+2R/R_Q)}{R^2C^2}}$
Band-pass	$\frac{\frac{s}{R_1C}}{s^2+s\frac{2}{R_QC}+\frac{(1+2R/R_Q)}{R^2C^2}}$

3.10.4 Soliman76 Family

In [17], an active second-order band-pass filter had been presented. The filter was proven to have minimized change in the natural frequency and selectivity due to finite amplifier gain and bandwidth. The filter schematics is shown in Fig. 22 with the transfer function in Table 19.

3.10.5 Soliman78 Family

In [18], an active second-order band-pass filter had been presented. The filter depends on activating two identical passive RC building blocks, which was proved to provide

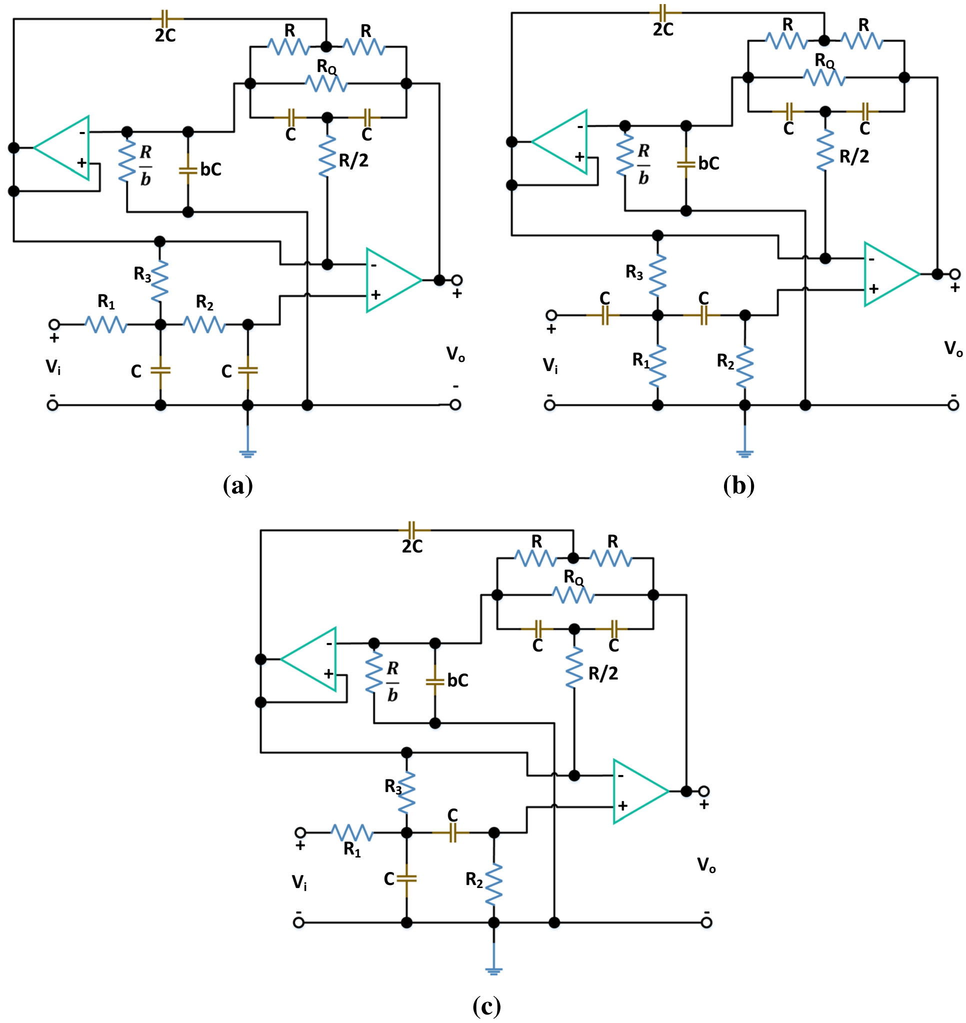


Fig. 14 Hamilton-Sedra72 IB Filters Family: **a** LPF, **b** HPF, **c** BPF [13]

Table 16 Hamilton-Sedra72 IC transfer functions

Filter type	$T(s)$
Band-pass ($k_2(1+k_3)=k_1k_3$)	$\dfrac{s\left(\frac{2R_4(R_5+R_6)}{R_QR_5(R_3+R_4)C}-\frac{R_2R_6(2R+4R_Q)}{R_QR_5(R_1+R_2)}\right)}{s^2+s\frac{2}{R_QC}+\frac{(1+2R/R_Q)}{R^2C^2}}$
All-pass ($k_2=k_3=1$)	$(\frac{2R_Q}{R+R_Q})\dfrac{s^2-s\frac{2}{R_QC}+\frac{(1+2R/R_Q)}{R^2C^2}}{s^2+s\frac{2}{R_QC}+\frac{(1+2R/R_Q)}{R^2C^2}}$
Notch ($k_2=k_3=1$)	$(\frac{4R_Q}{R+R_Q})\dfrac{s^2+\frac{(1+2R/R_Q)}{R^2C^2}}{s^2+s\frac{2}{R_QC}+\frac{(1+2R/R_Q)}{R^2C^2}}$

$k_1=\frac{R_2}{R_1+R_2}$, $k_2=\frac{R_4}{R_3+R_4}$, $k_3=\frac{R_6}{R_5}$

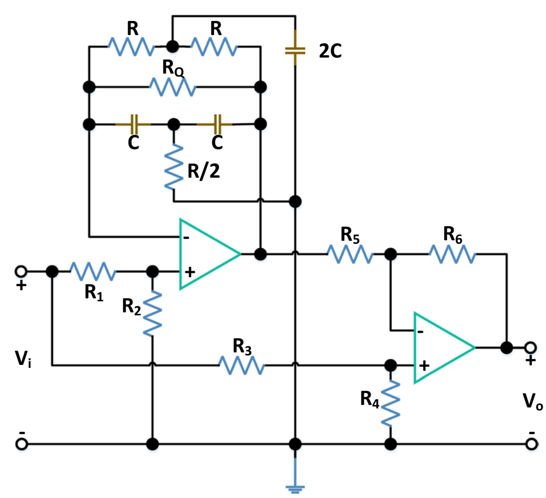


Fig. 15 Hamilton-Sedra72 IC Schematics [13]

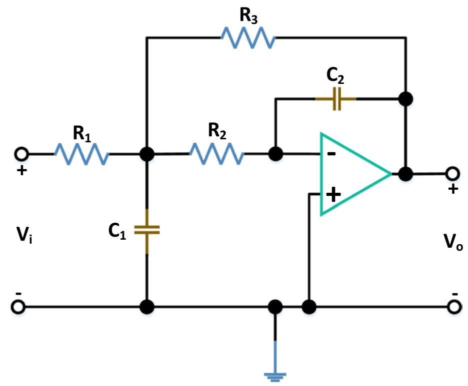


Fig. 16 Rauch Filter Schematics [45]

Table 17 Rauch, Geffe and TG Filter Transfer Functions

Filter type	$T(s)$
Low-pass (Rauch)	$\dfrac{\frac{-1}{R_1R_2C_1C_2}}{s^2+s(\frac{1}{R_1C_1}+\frac{1}{R_2C_1}+\frac{1}{R_3C_1})+\frac{1}{R_2R_3C_1C_2}}$
Band-pass (Geffe I)	$\dfrac{(\frac{1}{\frac{1}{K}-1})\frac{sR_3}{R_1R_2C_2(1+R_3)}}{s^2+s(\frac{1+R_1}{R_1C_2(1+R_3)}+\frac{1}{R_2C_1})+\frac{1+R_1}{R_1R_2C_1C_2(1+R_3)}}$
Low-pass (Geffe II)	$\dfrac{\frac{R_5+R_6}{R_1R_3R_5C_1C_2}}{s^2+s(\frac{R_5(R_3+R_4)-R_3(R_5+R_6)}{R_3R_4R_5C_2})+\frac{R_5+R_6}{R_2R_3R_5C_1C_2}}$
Band-pass (TG)	$\dfrac{K_1K_3K_4(1-T_1s)(1-T_2s)}{(1+K_2K_3K_4)T_1T_2s^2+(T_1+T_2)(1-K_2K_3K_4)Ts+(1+K_2K_3K_4)}$

a trade-off between better element ratios (spread of passive elements) and low sensitivity. The filter schematics are shown in Fig. 23 with the transfer function in Table 19.

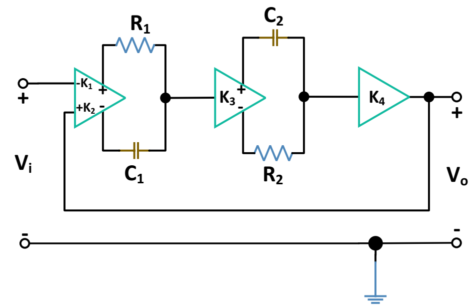


Fig. 18 Tarmy-Ghausi Filter Schematics [48]

3.10.6 Soliman79 Family

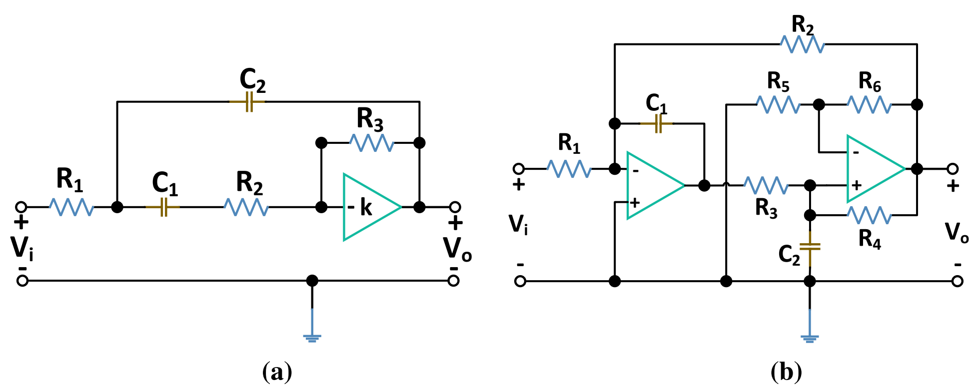
In [51], the author presented an active second-order canonic band-pass filter that is always stable and has low sensitivity to ω_t of the OA. The filter schematics are shown in Fig. 24 with the transfer function in Table 19.

3.11 Filters comparison and results

3.11.1 Filters features

Tables 20, 21 summarizes all the filters specifications. First, for Table 20, a set of key features for each filter alongside some shortcomings are presented. The shortcomings are assumed compared to the minimum required components to form a biquad circuit i.e., one opamp, two resistors, and two capacitors this is besides any disadvantage presented by the authors in the corresponding work. Second, for Table 21, the

Fig. 17 Geffe Filters Family: **a** BPF, **b** LPF [47]



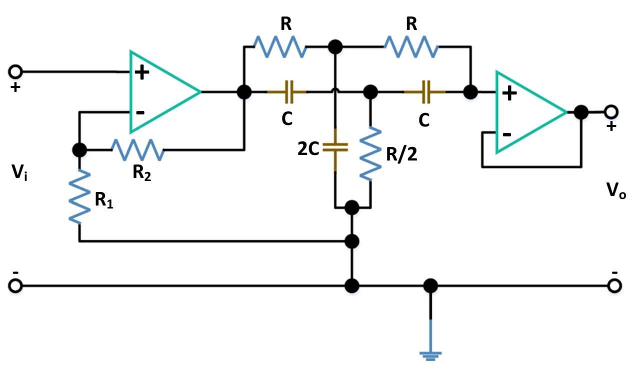


Fig. 19 Soliman72 Filter Schematics [49]

detailed passive sensitivity for each family was presented. The benefit of such a table arises when choosing among different designs. For example, in comparison between MB and BH LPF, while both use three opamps, the MB filter passive sensitivity for both R_3 and R_4 depends on their values, contrary to the BH filter where these resistors have a constant sensitivity. Finally, Table 22 shows a summary for the presented filters with some references in the literature and with the approximate effect of the roll-off of the operational amplifier gain beyond bandwidth. The active sensitivities of the filters presented assuming $Q_p >> 1$ and identical opamps for designs that use more than one amplifier. It's also worth mentioning that the effect of designing such filters on high CMOS technology nodes,i.e., 7nm, could be seen from two points of view according to this article, i.e., passive and

Table 18 Soliman73 Filter Transfer Functions

Filter type	$T(s)$
All-pass ($a = \frac{1}{1+1/2Q^2}$)	$a\dfrac{s^2-s(\frac{R_2(1-a)-2aR_3}{aR_2R_3C})+(\frac{\sqrt{R_3}}{\sqrt{R_2}R_3C})^2}{s^2+s(\frac{2}{R_2C})+(\frac{\sqrt{R_3}}{\sqrt{R_2}R_3C})^2}$
All-pass	$\dfrac{s^2-s(\frac{2R_2}{R_1R_3C})+(\frac{1}{R_3C})^2}{s^2+s(\frac{2(3R_4-R_5)}{R_3R_4C})+(\frac{1}{R_3C})^2}$

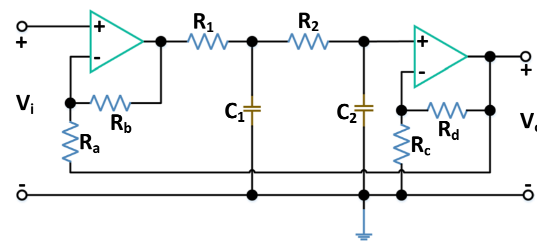


Fig. 21 Soliman74 Filter Schematics [15]

Table 19 Soliman76, Soliman78 and, Soliman79 Filter Transfer Functions

Filter type	$T(s)$
Band-pass (Soliman76)	$\dfrac{\frac{-as}{RC}}{s^2+s(\frac{b+1-a}{RC})+\frac{1}{R_2C_2}}$
Band-pass (Soliman78)	$\dfrac{\frac{-s}{R_2C}}{s^2+s(\frac{2-R_1/R_2}{R_1C})+\frac{1}{R_1R_2C^2}}$
Band-pass (Soliman79)	$\dfrac{\frac{-sa\beta}{R_1C_2}}{s^2+s(\frac{1}{R_1C_1}+\frac{1}{R_1C_2}-\frac{a}{R_2C_2})+\frac{1}{R_1R_2C_1C_2}}$

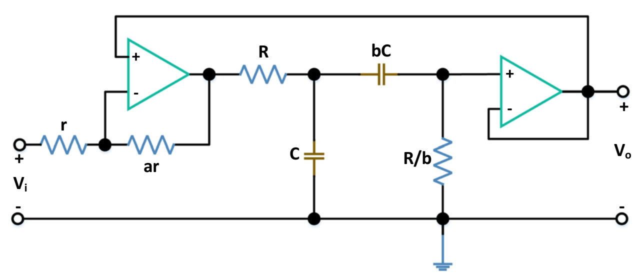


Fig. 22 Soliman76 Filter Schematics [17]

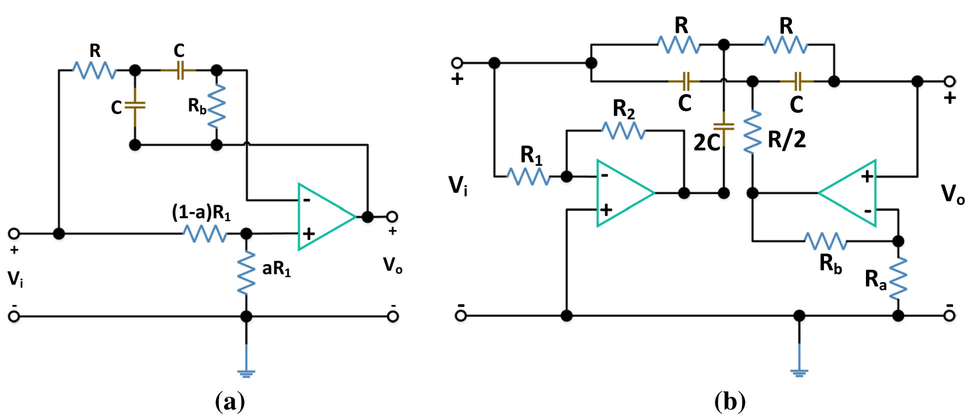


Fig. 20 Soliman73 Filters Family: **a** APF I, **b** APF II [50]

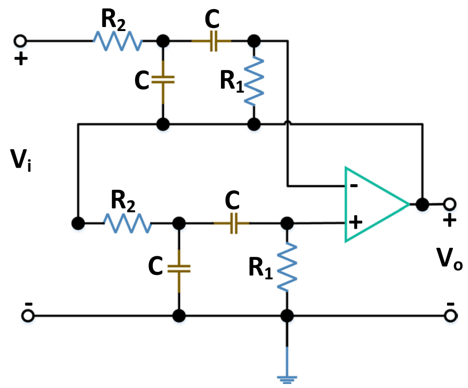


Fig. 23 Soliman78 Filter Schematics [18]

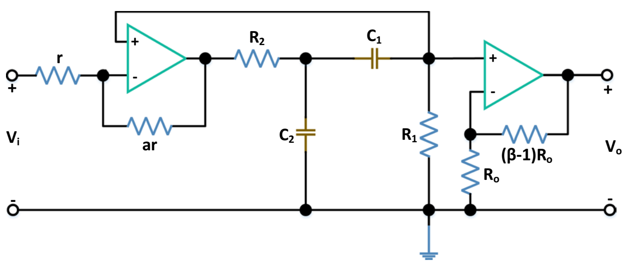


Fig. 24 Soliman79 Filter Schematics [51]

active sensitivities. For active sensitivity, some filters like KHN should not suffer from degradation if the DC-gain of the amplifier is high enough to minimize its input offset voltage. However, some filters that have a dependency on the DC-gain, i.e., the quality factor of Tow-Thomas, may suffer degradation depending on how the amplifier topology and variation on the gain. For passive sensitivity, and assuming the amplifier provides enough DC-gain, some filters specs should not be affected by the variations of the passive elements which depends on how they are implemented on IC technologies (i.e., poly resistors and MOM capacitors ...etc) like the cutoff frequency of Sallen-Key filters as shown in Table 21. Other filters have specs that are dependent on some of the passive element variations like the cutoff frequency of the MB filter as shown in Table 21.

3.11.2 Passive sensitivity simulation (Monte Carlo Results)

This section shows the monte-carlo results of some filter families to highlight a comparison among those filters for variations on the cutoff frequency. The monte-carlo analysis was performed on Cadence OrCAD software running 1000 monte-carlo seeds. The used amplifier model was TL084 which is based on BJT transistors with J-FET input pair in a monolithic integrated circuit. results were plotted using MATLAB software. The transfer function that is desired to simulate is as follows:

$$T(s) = \frac{K}{s^2 + \sqrt{2}s + 1}. \tag{13}$$

The realization of the filter assumed a frequency scaling by a factor of 1000 and a magnitude scaling by a factor of 10k to obtain realizable passive elements values. The scaling factors lead to a low-pass response with a cutoff frequency $\approx$ 159 Hz. The results are shown in Fig. 25. It could be seen that as expected from 21, both PMG and MB low-pass filters have high passive sensitivity contrary to Fliege and AM. The PMG and MB filters histograms show variations of $\approx$ 200 seeds which are 20% of the total seeds around 12.5% of the cutoff frequency while it is $\approx$ 150*seeds* for AM and is zero for Fliege.

The last result is a comparison among some different filters. However, for the seek of more understanding of the passive sensitivity analysis, a Monte Carlo analysis has been carried out on the same filter but with varying tolerance of the passive components. PMG filter was chosen in three cases; no tolerance for all passive elements, 10% tolerance for R_5 and, 10% tolerance for R_7. From Table 21 it could be seen that in case of $R_7 = R_8$ the passive sensitivity of the cutoff frequency to R_5 and R_7 is 0.5 and 0.25 respectively. This means the spread of the cutoff frequency along the Monte Carlo seeds is higher in the case of tolerance R_5. Figure 26 shows these results. It could be seen that in case of no tolerance there are no variations on the cutoff frequency, while variation is 120:210 Hz for R_5 and, 140 : 180 Hz for R_7 which, as expected, is lower than that of R_5.

Table 20 Filters Specifications

Family name	Key feature	Shortcomings
Sallen-Key	Minimum passive components Ease of direct cascading	Moderate passive sensitivity
KHN	Multiple response Low passive and active sensitivity Minimum number of capacitors	Uses 3 opamps Uses 8 passive elements
TT	Multiple response Low passive and active sensitivity Minimum number of capacitors	Uses 3 opamps Uses 8 passive elements
Bach	Minimum passive components Ease of direct cascading Low spread of passive elements	Need for iterative procedure to design
Fliege	Low spread of elements Relative sensitivities to the passive elements are of the same order of magnitude as that of a second-order passive network Pole parameters have low active sensitivities	Many passive components (i.e. 7 $\sim$ 8) which implies more complexity and more power consumption
MB	Low passive sensitivity Very low active sensitivity Adjustable universal design Suitable for high-Q realizations Insensitive to temperature and power supply No isolation OPAMP is needed for cascading Low resistors spread	Uses 3 OPAMPs Uses 10 passive elements
BH	Universal building block Low active sensitivity	Uses 3 OPAMPs Uses 9 $\sim$ 10 passive components
PMG	High Q at high frequencies Low sensitivity for passive and active components Low sensitivity for GB which cut the need for matched OPAMPs	Uses 3 OPAMPs Uses 10 passive elements
Deliyannis	SAB High Q at high frequencies	Large spread of elements for positive feedback section
Soliman72	Medium selectivity Very low passive sensitivities	Double OPAMPs 8 passive components
AM	Universal building block Quality factor is approximately independent of the gain-bandwidth product of the operational amplifiers low temperature sensitivity for quality factor	Uses 3 OPAMPs Uses 9 $\sim$ 10 passive components Capacitive input for HPF and BPF
Soliman73I	SAB Always stable	–
Soliman73II	Provides unity gain factor	Double OPAMPs 10 passive components
Soliman74	ω_o is insensitive to ω_t	Double OPAMPs 8 passive components
Soliman76	Canonic design Provides gain High quality factor low active sensitivity low sensitivity to ω_t of the OAs	Double OPAMP 6 passive components high passive sensitivity
Soliman78	Canonic design SAB Low active sensitivity Low passive sensitivity low sensitivity to ω_t of the OAs	Two passive RC networks Trade-off between spread of passive elements and low passive sensitivity
Soliman79	Inverting canonic design Always stable Low sensitivity to amplifier gain-bandwidth product	Double OPAMP 8 passive components

Table 20 (continued)

Family name	Key feature	Shortcomings
HS72 IA	SAB Low quality factor ($Q \leq 50$)	11 passive components Based on pole-zero cancellation technique Quality factor active sensitivity limits the maximum quality factor ($S^{Q}_{A_o} \simeq \frac{6Q}{A_o}$)
HS72 IB	Medium quality factor ($50 < Q \leq 500$)	Double OPAMPs 14 passive components Based on pole-zero cancellation technique
HS72 IC	Easily cascadable High resistive input impedance Low resistive output impedance APF uses less OPAMPs compared to Moschytz70 for the same quality factor	Double OPAMPs 14 passive components Based on pole-zero cancellation technique
Geffe I	SAB low passive sensitivity Moderate quality factor	Band-pass only floating capacitors
Geffe II	Low quality factor Low passive sensitivity	Double OPAMPs 8 passive elements High quality factor active sensitivity except for low quality factor
Soderstand	Zero passive sensitivity Active sensitivity less than 0.5	Double OPAMPs
TG	High Q low passive sensitivity	Triple OPAMPs

3.11.3 Simulation results for the active sensitivity of the cutoff frequency

To check the active sensitivity of a filter, it is desired to check the change of the cutoff frequency due to the degradation of the dc gain of the used amplifier. As every amplifier has a common-mode input range, a sweep on the VCM will first be simulated to identify the operating range of the used opamp (i.e., TL084). The simulation was carried on OrCAD software, and the result is shown in Fig 27. As the BJT-based amplifier suffers an abrupt degradation in DC gain outside its common-mode input range, this could be seen around $\pm 13V$. This means that a sweep on VCM could be used as a reflector of the deviation on the DC gain of the opamp.

Four filters families were simulated to realize the transfer function in .13 with the same magnitude and frequency scaling as the Monte Carlo analysis. A parametric sweep on the input common-mode was performed over the ac analysis on OrCAD; then, the measurement of the 3-dB frequency was taken and plotted over the sweep using MATLAB. Figure 28 shows the sweep results. The expected cutoff frequency of the transfer function should be at 159 Hz as could be seen from the figure that AM and MB filters have a better response (stable over higher ranger of VCM) than BH and Fliege. This result agrees with the listed active sensitivity in Table 22.

3.11.4 Cutoff frequency active sensitivity experimental results

To check the effect of the active sensitivity on the cutoff frequency experimentally, MB filter is chosen and designed to synthesize the transfer function in 13 with 10000 magnitude scale and 10000 frequency scale. The expected cutoff frequency should be at 1.59 KHz . The experiment was carried out using NI ELVIS II kit. The LM324A chip was used for the opamps in the filter. The calculated passive elements are $R_1 = R_3 = R_4 = R_5 = R_8 = 14\ K\Omega$, $R_6 = R_7 = 10\ K\Omega$ and, `It could be seen in Fig. 29(b) that the cutoff frequency around $VCM = 0\ V$ is $f_o \approx 1585\ Hz$ while a little degradation

Table 21 Passive sensitivity For the stated filters families

Family	Filter Type	y	S_x^y											
			R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	C_1	C_2	C_3
SK	LPF	ω_o	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	–	–	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	*SKQ1	*SKQ2	–	–	–	–	–	–	–	*SKQ3	*SKQ4	–
Rauch	LPF	ω_o	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	–	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	*Rauch1	*Rauch2		–	–	–	–	–	–	$\frac{-1}{2}$	$\frac{1}{2}$	–
Bach	LPF	ω_o	$\frac{1}{2}$	$\frac{1}{2}$	–	–	–	–	–	–	–	$\frac{1}{2}$	$\frac{1}{2}$	–
		Q	$\frac{-1}{2}$	$\frac{1}{2}$	–	–	–	–	–	–	–	$\frac{-1}{2}$	$\frac{1}{2}$	–
Geffe	LPF1	ω_o	$\frac{-1/2}{1+R_1}$	$\frac{-1}{2}$	$\frac{-R_3}{2(1+R_3)}$	–	–	–	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	*Ge1R1	*Ge1R2	*Ge1R3	–	–	–	–	–	–	*Ge1C1	*Ge1C2	–
	LPF2	ω_o	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–	$\frac{-R_6}{2(R_5+R_6)}$	$\frac{R_6}{2(R_5+R_6)}$	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	–	*Ge2R2	*Ge2R3	*Ge2R4	*Ge2R5	*Ge2R6	–	–	–	*Ge2C1	$\frac{-1}{2}$	–
Fliege	LPF	ω_o	$\frac{1}{2}$	$\frac{-1}{2}$	$\frac{-1}{2}$	–	$\frac{-1}{2}$	–	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	$\frac{1}{2}$	$\frac{-1}{2}$	$\frac{-1}{2}$	1	$\frac{-1}{2}$	–	–	–	–	$\frac{-1}{2}$	$\frac{1}{2}$	–
	HPF	ω_o	$\frac{-1}{2}$	$\frac{1}{2}$	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	$\frac{-1}{2}$	$\frac{1}{2}$	$\frac{-1}{2}$	$\frac{-1}{2}$	1	–	–	–	–	$\frac{-1}{2}$	$\frac{1}{2}$	–
	BPF	ω_o	$\frac{-1}{2}$	$\frac{1}{2}$	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	$\frac{-1}{2}$	$\frac{1}{2}$	$\frac{-1}{2}$	$\frac{-1}{2}$	1	–	–	–	–	$\frac{-1}{2}$	$\frac{1}{2}$	–
	NF	ω_o	$\frac{-1}{2}$	$\frac{1}{2}$	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	$\frac{-1}{2}$	$\frac{1}{2}$	$\frac{-1}{2}$	$\frac{-1}{2}$	$\frac{R_5}{R_5+R_6}$	$\frac{R_6}{R_5+R_6}$	–	–	–	$\frac{-1}{2}$	$\frac{1}{2}$	–
KHN	U	ω_o	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	–	–	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	$\frac{1}{2}$	$\frac{-1}{2}$	*KHQ1	*KHQ2	–	–	–	–	–	$\frac{1}{2}$	$\frac{-1}{2}$	–
TT	U	ω_o	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	–	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	1	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	–	–	–	–	$\frac{1}{2}$	$\frac{-1}{2}$	–
MB	LPF	ω_o	$\frac{1}{2}$	–	$\frac{-R_4}{R_3+R_4}$	$\frac{-R_3}{R_3+R_4}$	$\frac{-1}{2}$	–	–	$\frac{-1}{2}$	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	$\frac{-1}{2}$	1	$\frac{-R_4/2}{R_3+R_4}$	$\frac{-R_3/2}{R_3+R_4}$	$\frac{1}{2}$	1	-1	$\frac{-1}{2}$	–	$\frac{1}{2}$	$\frac{-1}{2}$	–
	HPF	ω_o	$\frac{R_2/2}{R_1+R_2}$	$\frac{R_1/2}{R_1+R_2}$	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	$\frac{-1}{2}$	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	$\frac{-R_2/2}{R_1+R_2}$	$\frac{-R_1/2}{R_1+R_2}$	1	$\frac{-1}{2}$	$\frac{1}{2}$	1	-1	$\frac{-1}{2}$	–	$\frac{1}{2}$	$\frac{-1}{2}$	–
	BPF	ω_o	$\frac{1}{2}$	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	$\frac{-1}{2}$	$\frac{R_2}{1+R_2R_3}$	$\frac{R_3}{1+R_2R_3}$	$\frac{-1}{2}$	$\frac{1}{2}$	1	-1	$\frac{-1}{2}$	–	$\frac{1}{2}$	$\frac{-1}{2}$	–
	NF	ω_o	$\frac{R_2/2}{R_1+R_2}$	$\frac{R_1/2}{R_1+R_2}$	–	$\frac{-1}{2}$	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	$\frac{-R_2/2}{R_1+R_2}$	$\frac{-R_2/2}{R_1+R_2}$	1	$\frac{-R_5/2}{R_4+R_5}$	$\frac{-R_4/2}{R_4+R_5}$	$\frac{1}{2}$	1	-1	$\frac{-1}{2}$	–	$\frac{1}{2}$	$\frac{-1}{2}$
PMG	LPF	ω_o	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	$\frac{1}{2}$	$\frac{-R_8/2}{R_7+R_8}$	$\frac{-R_7/2}{R_7+R_8}$	–	$\frac{-C_1/2}{C_1+C_2}$	$\frac{-C_2/2}{C_1+C_2}$	–
		Q	1	-1	1	$\frac{1}{2}$	$\frac{-1}{2}$	$\frac{-1}{2}$	$\frac{-R_8/2}{R_7+R_8}$	$\frac{-R_7/2}{R_7+R_8}$	–	$\frac{1}{2}$	$\frac{-1}{2}$	–
	HPF	ω_o	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	$\frac{1}{2}$	$\frac{-1}{2}$	–	–	$\frac{-C_1/2}{C_1+C_2}$	$\frac{-C_2/2}{C_1+C_2}$	–
		Q	1	-1	1	$\frac{1}{2}$	$\frac{-1}{2}$	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	$\frac{C_1/2}{C_1+C_3}$	$\frac{-1}{2}$	$\frac{C_3/2}{C_1+C_3}$
	BPF	ω_o	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	$\frac{1}{2}$	$\frac{-1}{2}$	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	1	-1	1	$\frac{1}{2}$	$\frac{-1}{2}$	$\frac{-1}{2}$	$\frac{-R_8/2}{R_7+R_8}$	$\frac{-R_7/2}{R_7+R_8}$	–	$\frac{1}{2}$	$\frac{-1}{2}$	–
	NF	ω_o	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	$\frac{1}{2}$	$\frac{-R_8/2}{R_7+R_8}$	$\frac{-R_7/2}{R_7+R_8}$	–	$\frac{-C_1/2}{C_1+C_3}$	$\frac{-1}{2}$	$\frac{-C_3/2}{C_1+C_3}$
		Q	1	-1	1	$\frac{1}{2}$	$\frac{-1}{2}$	$\frac{-1}{2}$	$\frac{-R_8/2}{R_7+R_8}$	$\frac{-R_7/2}{R_7+R_8}$	–	$\frac{C_1/2}{C_1+C_3}$	$\frac{-1}{2}$	$\frac{C_3/2}{C_1+C_3}$

Table 21 (continued)

Family	Filter Type	y	S_x^y											
			R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	C_1	C_2	C_3
BMA	LPF I	ω_o	$\frac{-1}{2}$	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	$\frac{-1}{2}$	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	$\frac{-1}{2}$	–	1	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	$\frac{-1}{2}$	–	$\frac{-1}{2}$	$\frac{1}{2}$	–
	LPF II	ω_o	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	$\frac{1}{2}$	$\frac{-R_8/2}{R_7+R_8}$	$\frac{-R_7/2}{R_7+R_8}$	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	–	*BMA1	*BMA2	–	*BMA3	$\frac{-R_8/2}{R_7+R_8}$	$\frac{-R_7/2}{R_7+R_8}$	–	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{-1}{1+\frac{R_2R_3C_1}{R_4R_6C_8}}$	
	HPF I	ω_o	$\frac{-1}{2}$	$\frac{1}{2}$	–	$\frac{-1}{2}$	–	$\frac{-1}{2}$	–	–	–	$\frac{-1}{2}$	$\frac{-C_7/2}{C_7+C_8}$	$\frac{-C_8/2}{C_7+C_8}$
		Q	$\frac{-1}{2}$	$\frac{1}{2}$	–	$\frac{-1}{2}$	–	$\frac{-1}{2}$	–	1	–	$\frac{-1}{2}$	$\frac{C_7/2}{C_7+C_8}$	$\frac{C_8/2}{C_7+C_8}$
	HPF II	ω_o	$\frac{-1}{2}$	$\frac{1}{2}$	–	$\frac{-1}{2}$	–	$\frac{-1}{2}$	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	$\frac{1}{2}$	$\frac{-1}{2}$	–	$\frac{1}{2}$	–	$\frac{1}{2}$	-1	–	–	$\frac{1}{2}$	$\frac{-1}{2}$	–
	BPF I	ω_o	$\frac{-1}{2}$	–	–	$\frac{-1}{2}$	–	$\frac{-1}{2}$	–	$\frac{1}{2}$	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	$\frac{1}{2}$	–	–	$\frac{1}{2}$	–	$\frac{-1}{2}$	–	$\frac{-1}{2}$	–	$\frac{1}{2}$	$\frac{1}{2}$	-1
	BPF II	ω_o	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	$\frac{1}{2}$	–	$\frac{-1}{2}$	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	–	*BMA4	$\frac{-1}{1+\frac{R_2R_3C_1}{R_4R_6C_7}}$	–	$\frac{1}{2}-\frac{1}{1+\frac{R_2R_3C_1}{R_4R_6C_7}}$	–	$\frac{-1}{2}$	–	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{-1}{1+\frac{R_2R_3C_1}{R_4R_6C_7}}$	
	BPF III	ω_o	$\frac{-1}{2}$	–	$\frac{-1}{2}$	–	$\frac{-1}{2}$	–	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	$\frac{-1}{2}$	$\frac{1}{2}$	–	$\frac{-1}{2}$	–	$\frac{-1}{2}$	$\frac{R_8}{R_7+R_8}$	$\frac{R_7}{R_7+R_8}$	–	$\frac{-1}{2}$	$\frac{1}{2}$	–
	NF I	ω_o	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–	$\frac{1}{2}$	–	$\frac{-1}{2}$	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	–	$\frac{1}{2}$	$\frac{1}{2}$	–	$\frac{-1}{2}$	–	$\frac{-1}{2}$	–	–	$\frac{1}{2}$	$\frac{1}{2}$	-1
	NF II	ω_o	$\frac{-1}{2}$	$\frac{1}{2}$	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	$\frac{-1}{2}$	$\frac{1}{2}$	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	1	–	$\frac{-1}{2}$	$\frac{1}{2}$	–
	NF III	ω_o	$\frac{-1}{2}$	$\frac{1}{2}$	–	$\frac{-1}{2}$	$\frac{-R_6/2}{R_5+R_6}$	$\frac{-R_5/2}{R_5+R_6}$	–	–	–	–	$\frac{-C_7}{C_7+C_8}$	$\frac{-C_8}{C_7+C_8}$
		Q	$\frac{-1}{2}$	$\frac{1}{2}$	–	–	$\frac{-R_6/2}{R_5+R_6}$	$\frac{-R_5/2}{R_5+R_6}$	–	1	–	–	$\frac{-C_7/2}{C_7+C_8}$	$\frac{-C_8/2}{C_7+C_8}$
Deliyannis	BPF I	ω_o	$\frac{-R_3/2}{R_1+R_3}$	$\frac{-1}{2}$	$\frac{-R_1/2}{R_1+R_3}$	–	–	–	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	$\frac{-R_3/2}{R_1+R_3}$	$\frac{1}{2}$	$\frac{-R_1/2}{R_1+R_3}$	–	–	–	–	–	–	$\frac{C_2-C_1}{2(C_1+C_2)}$	$\frac{C_1-C_2}{2(C_1+C_2)}$	–
	BPF II	ω_o	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	–	–	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	*DelR1	*DelR2	*DelR3	*DelR3	–	–	–	–	–	*DelC1	*DelC2	–
Soderst rand-Mitra	BPF	ω_o	-1	-1	–	–	–	–	–	–	–	-1	-1	–
		Q	*Sod1	*Sod2	–	–	–	–	–	–	–	*Sod1	*Sod2	–
Soliman72	Notch	ω_o	–	–	-1	–	–	–	–	–	–	-1	–	–
		Q	-1	1	–	–	–	–	–	–	–	–	–	–
Soliman73I	All-pass	ω_o	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	–	–	–	–	-1	–	–
		Q	$\frac{1}{2}$	$\frac{-1}{2}$	–	–	–	–	–	–	–	–	–	–
Soliman73II	All-pass	ω_o	–	–	-1	–	–	–	–	–	–	-1	–	–
		Q	–	–	–	*Sol73a	*Sol73b	–	–	–	–	–	–	–
Soliman74	Low-pass	ω_o	$\frac{-1}{2}$	$\frac{-1}{2}$	$> \frac{-1}{2}$	$< \frac{1}{2}$	$> \frac{-1}{2}$	$< \frac{1}{2}$	-	-	-	$\frac{-1}{2}$	$\frac{-1}{2}$	-
		Q	$\frac{-1}{6}$	$\frac{-1}{6}$	$> \frac{-1}{2}$	$< \frac{1}{2}$	$> \frac{-1}{2}$	$< \frac{1}{2}$	-	-	-	$\frac{1}{6}$	$\frac{1}{6}$	-
Soliman76	Band-pass	ω_o	-1	–	–	–	–	–	–	–	–	-1	–	–
		Q	–	–	–	–	–	–	–	–	–	–	–	–
Soliman78	Band–pass	ω_o	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	–	–	–	–	–	-1	–	–
		Q	*Sol78a	*Sol78b	–	–	–	–	–	–	–	–	–	–

Table 21 (continued)

Family	Filter Type	y	S_x^y											
			R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	C_1	C_2	C_3
Soliman79	Band-pass	ω_o	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	–	–	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	*Sol79a	*Sol79b	–	–	–	–	–	–	–	*Sol79c	*Sol79d	–
AM	LPF	ω_o	–	$\frac{-1}{2}$	$\frac{1}{2}$	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	–	$\frac{-1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{-1}{2}$	1	–	–	–	$\frac{-1}{2}$	$\frac{1}{2}$	–
	HPF	ω_o	–	$\frac{-1}{2}$	$\frac{1}{2}$	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	–	$\frac{-1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{-1}{2}$	1	–	–	–	$\frac{-1}{2}$	$\frac{1}{2}$	–
	BPF	ω_o	–	$\frac{-1}{2}$	$\frac{1}{2}$	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	–	$\frac{-1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{-1}{2}$	1	–	–	–	$\frac{-1}{2}$	$\frac{1}{2}$	–
	NF	ω_o	–	$\frac{-1}{2}$	$\frac{1}{2}$	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	–	$\frac{-1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{-1}{2}$	1	–	–	–	$\frac{-1}{2}$	$\frac{1}{2}$	–
BH	LPF	ω_o	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	$\frac{-1}{2}$	$\frac{1}{2}$	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	$\frac{-1}{2}$	$\frac{-1}{2}$	1	–	$\frac{-1}{2}$	$\frac{1}{2}$	–	–	–	$\frac{1}{2}$	$\frac{-1}{2}$	–
	HPF	ω_o	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	$\frac{-1}{2}$	$\frac{1}{2}$	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	$\frac{-1}{2}$	$\frac{-1}{2}$	1	–	$\frac{-1}{2}$	$\frac{1}{2}$	–	–	–	$\frac{1}{2}$	$\frac{-1}{2}$	–
	BPF	ω_o	$\frac{-1}{2}$	$\frac{-1}{2}$	–	–	$\frac{-1}{2}$	$\frac{1}{2}$	–	–	–	$\frac{-1}{2}$	$\frac{-1}{2}$	–
		Q	$\frac{-1}{2}$	$\frac{-1}{2}$	1	–	$\frac{-1}{2}$	$\frac{1}{2}$	–	–	–	$\frac{1}{2}$	$\frac{-1}{2}$	–

*SKQ1: $-0.5+Q$, *SKQ2: $0.5-Q$, *SKQ3: $-0.5+2Q$, *SKQ4: $-0.5-2Q$

*Rauch1: $\frac{R_1}{1+R_1(C_1/R_2C_2+1/R_3)}$

*Rauch2: $\frac{1/\sqrt{R_2}-\sqrt{R_2}(C_2/R_1C_1+C_2/R_3C_1)}{2\sqrt{R_2R_3C_1/C_2}[1/\sqrt{R_2}+\sqrt{R_2}(C_2/R_1C_1+C_2/R_3C_1)]}$

*Ge1R1: $\frac{1}{2\sqrt{R1}}-\frac{R_1[R_2C_1+C_2(1+R_3)]}{R_2C_1(1+R_1)+R_1C_2(1+R_3)}$

*KHQ1: $\frac{-1}{1+R_3/R_4}$, *KHQ2: $\frac{1}{1+\frac{1}{R_3R_4}}$

*Ge1R2: $\frac{R_1C_2(1+R_3)}{R_2C_1(1+R_1)+R_1C_2(1+R_3)}$, *Ge1R3: $\frac{R_2R_3C_1(1+R_1)(1+R_3)}{R_1C_2(1+R_3)+R_2C_1(1+R_1)}$

*Ge1C1: $\frac{R_1C_2(1+R_3)}{R_2(1+R_1)C_1+R_1C_2(1+R_3)}$, *Ge1C2: $\frac{R_2C_1(1+R_1)}{R_1(1+R_3)C_2+R_2C_1(1+R_1)}$

*Ge2R2: $\frac{-\sqrt{R_1}}{2R_3(R_5+R_6)\sqrt{C_1}\{R_5(R_3+R_4)-R_3(R_5+R_6)\sqrt{R_2C_1}\}}$

*Ge2R3: $0.5-\frac{R_3\{R_5-(R_5+R_6)\sqrt{R_2C_1}\}}{R_5(R_3+R_4)-R_3(R_5+R_6)\sqrt{R_2C_1}}$

*Ge2R4: $1-\frac{R_4R_5}{R_5(R_3+R_4)-R_3(R_5+R_6)\sqrt{R_2C_1}}$

*Ge2R5: $1-\frac{R_6}{2(R_5+R_6)}-\frac{R_5\{R_4+R_3(1-\sqrt{R_2C_1})\}}{R_5(R_3+R_4)-R_3(R_5+R_6)\sqrt{R_2C_1}}$

*Ge2R6: $\frac{R_6}{2(R_5+R_6)}-\frac{R_3R_6\sqrt{R_2C_1}}{R_5(R_3+R_4)-R_3(R_5+R_6)\sqrt{R_2C_1}}$

*Ge2C1: $\frac{0.5R_3(R_5+R_6)\sqrt{R_2C_1}}{R_5(R_3+R_4)-R_3(R_5+R_6)\sqrt{R_2C_1}}$

*BMA1: $\frac{1}{2}-\frac{1}{1+\frac{R_4R_6C_8}{R_2R_3C_1}}$, *BMA2: $\frac{1}{1+\frac{R_4R_6C_8}{R_2R_3C_1}}$, *BMA3: $\frac{1}{2}-\frac{1}{1+\frac{R_2R_3C_1}{R_4R_6C_8}}$, *BMA4: $\frac{1}{2}-\frac{1}{1+\frac{R_4R_6C_7}{R_2R_3C_1}}$

*DelR1: $\frac{1}{2}-\frac{1}{1+\frac{R_2R_aC_1}{R_1R_b(C_1+C_2)}}$, *DelR2: $\frac{1}{2}-\frac{1}{1+\frac{R_1R_b(C_1+C_2)}{R_2R_aC_1}}$, *DelR3: $\frac{1}{1+\frac{R_1R_b(C_1+C_2)}{R_2R_aC_1}}$

*DelR4: $\frac{1}{2}-\frac{1}{1+\frac{R_2R_aC_1}{R_1R_b(C_1+C_2)}}$

*DelC1: $\frac{1}{2}-\frac{1}{1+\frac{R_1R_bC_2}{R_1R_b+R_2R_a}}$, *DelC2: $\frac{1}{2}-\frac{1}{1+\frac{R_1R_b+R_2R_a}{R_1R_bC_2}}$

*Sod1: $\frac{R_2C_2-R_1C_1}{2(R_1C_1+R_2C_2)}$, *Sod2: $\frac{R_1C_1-R_2C_2}{2(R_1C_1+R_2C_2)}$

Table 21 (continued)

*Sol73a: $\frac{-R_5}{3R_4-R_5}$, *Sol73b: $\frac{R_5}{3R_4-R_5}$

*Sol78a: $\frac{2}{2-R_1/R_2}$, *Sol78b: $-0.5-\frac{R_1/R_2}{2-R_1/R_2}$

*Sol79a: $\frac{aR_2C_2}{R_1C_1+R_1C_2+aR_2C_2}$, *Sol79b: $\frac{aC_2}{R_1C_1+R_1C_2+aR_2C_2}$

*Sol79c: $\frac{R_1}{R_1C_1+R_1C_2+aR_2C_2}$, *Sol79d: $\frac{R_1+aR_2}{R_1C_1+R_1C_2+aR_2C_2}$

Table 22 Filters Summary

Family name	Ref	No. of OAs	No. of Rs	No. of Cs	Approximate Bandwidth Limitations		Active sensitivity	
					$\frac{\Delta\omega_o}{\omega_o}/\frac{\omega_o}{\omega_t}$	$\frac{\Delta Q}{Q}/\frac{\omega_o}{\omega_t}$	$S^{\omega_o}_{A_o}$	$S^{Q_p}_{A_o}$
Sallen-Key	[31]	1	2	2	$-\frac{1}{2}(3-\frac{1}{Q})^2$	$-\frac{1}{2}(3-\frac{1}{Q})^2$	$12.5Q_p^2$	$12.5Q_p^2$
Rauch	[45]	1	3	2	$\frac{-3Q}{2}$	$\frac{Q}{2}$	N/A	N/A
Bach	[32]	2	2	2	$\frac{-1}{2Q(\omega_t)}$	$\frac{-1}{2Q(\omega_t)}$	N/A	N/A
KHN	[10, 22, 38]	3	6	2	-1	$4Q_p$	$\star 1/3$	$\star 1/3$
Tow-Thomas	[22, 39, 40]	3	6	2	$1+\frac{2\omega_o}{\omega_t}$	$1-\frac{4\omega_o}{\omega_t}$	0	$\frac{2Q_p}{A_o}$
Tarmy-Ghausi	[16, 48] [19]	3	2	2	$1+\frac{3\omega_o}{\omega_t}$	$1+\frac{3Q}{A_o}-\frac{3\omega_o}{2\omega_t}$	0	$\frac{3Q_p}{A_o}$
Soliman72	[49]	2	5	3	$-2+\frac{1}{2Q}$	$2-\frac{1}{2Q}$	0	$\frac{4Q_p}{A_o}$
Soliman73I	[50]	1	4	2	$1-\frac{\omega_o Q}{\omega_t}$	$1+\frac{\omega_o Q}{\omega_t}$	0	$\frac{2Q_p^2}{A_o}$
Soliman73II	[50]	3	7	3	$1-\frac{4\omega_o Q}{\omega_t}$	$1+\frac{4\omega_o Q}{\omega_t}$	0	$<\frac{8Q_p}{A_o}$
Soliman74	[15]	2	6	2	0	$6Q^2$	$\frac{3Q_p}{A_o}$	$\frac{3Q_p}{A_o}$
Soliman76	[17]	2	4	2	$\frac{3}{\omega_o}$	$\frac{6\omega_t}{A\omega_o}-\frac{3}{Q}$	N/A	N/A
Soliman78	[18]	1	4	4	-1.4	-1.4	0	$\frac{2Q_p}{A_o}$
Soliman79	[51]	2	6	2	-2	2	N/A	N/A
Fliege	[6, 35]	2	5	2	-2	$-2Q(\frac{2\omega_t}{A_o\omega_o}+1)$	N/A	N/A
AM	[14, 42]	3	6	2	$\frac{3\omega_o}{2\omega_t}$	$\frac{3Q}{A_o}+\frac{\omega_o}{2\omega_t}$	$\frac{\omega_o}{\omega_t}$	$\frac{Q_p\omega_o}{\omega_t}$
MB	[16]	3	9	2	$1+\frac{\omega_o}{\omega_t}$	$1+\frac{Q}{A_o}-\frac{\omega_o}{2\omega_t}$	0	$\frac{Q_p}{A_o}$
PMG	[19]	3	8	3~4	$\frac{2\omega_o}{\omega_t}$	$\frac{-2\omega_o}{\omega_t}$	0	$\frac{2Q_p-1}{A_o}$
BH	[21]	3	~9	2	N/A	N/A	0.5	$6Q_p^2+0.5$
BMA	[30]	2	~6	~3	$\omega_o(1-2\omega_o/\omega_t)$	$Q_p(1-4Q_p/A_o)$	$\frac{-1}{A_oQ_p}$	$\frac{4Q_p}{A_o}$
Deliyannis	[36]	1	~4	~2	N/A	N/A	0	$\frac{Q_p}{A_o}\sqrt{\frac{R_2}{R_1}}$
AM	[41, 42]	3	~6	~3	0.5	1	$\frac{\omega_o}{\omega_t}$	$Q_p\frac{\omega_o}{\omega_t}$
Hamilton-Sedra (IA)	[13]	1	6	5	*HS1dw	*HS1dQ	0	$\frac{4Q_p}{A_o}$
Hamilton-Sedra (IB)	[13]	2	8	6	*HS2dw	*HS2dQ	0	$\frac{0.4Q_p}{A_o}$
Hamilton-Sedra (IC)	[13]	2	10	3	N/A	N/A	0	$\frac{4Q_p}{A_o}$
Geffe II	[47]	2	6	2	N/A	N/A	0	$\frac{-2Q_p}{A_o-2}$

⋆ Pole sensitivity to the amplifier gain.

*HS1dQ $=\frac{\omega_t}{\omega_o}(\frac{1}{\sqrt{1+4\omega_o/\omega_t}}-1)$

*HS1dQ $=\frac{\omega_t}{\omega_o}(\frac{1}{1+\frac{4Q_p}{A_o}+4Q_p(\omega_o/\omega_t)^2+2(\omega_o/\omega_t)}-1)$

*HS2dw $=\frac{\omega_t}{\omega_o}(\frac{1}{\sqrt{1+0.4\omega_o/\omega_t}}-1)$

*HS2dQ $\frac{\omega_t}{\omega_o}(\frac{1}{1+\frac{0.4Q_p}{A_o}+0.4Q_p(\omega_o/\omega_t)^2+0.2(\omega_o/\omega_t)}-1)$

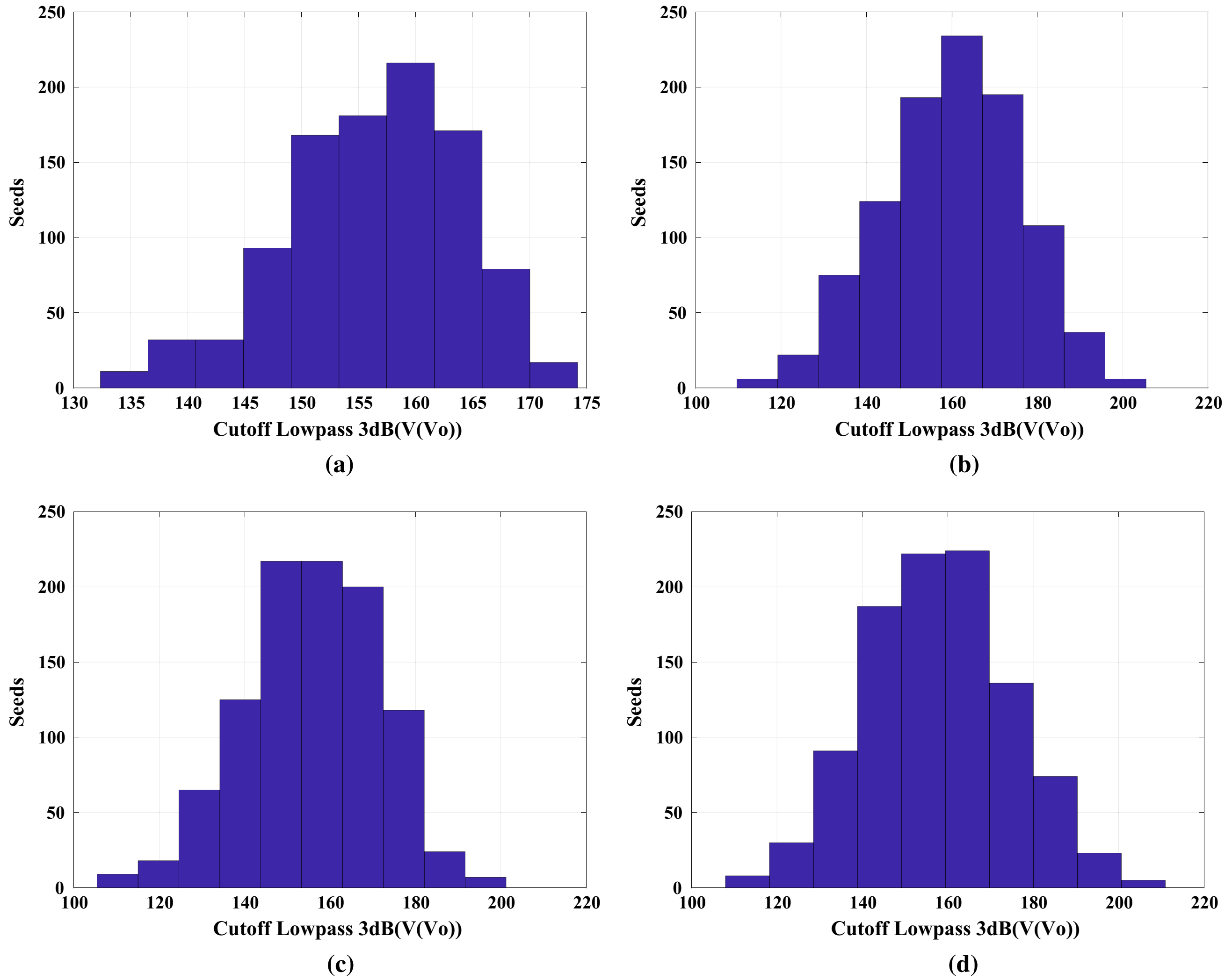


Fig. 25 Monte Carlo results histogram for some filters families: **a** Fliege, **b** MB, **c** PMG, **d** AM

on the input common-mode level (i.e., $VCM = 0.5\ V$) causes a degradation on the DC gain of the amplifiers thus the cut-off frequency is $f_o \approx 1230\ Hz$ and finally for a relatively high input common-mode $VCM = 2\ V$ the filter fails and the output is messy.

4 Conclusion

This work is a review article for active and passive sensitivities analysis of some second-order analog active filters based on opamp in the literature. As can be seen, there are a lot

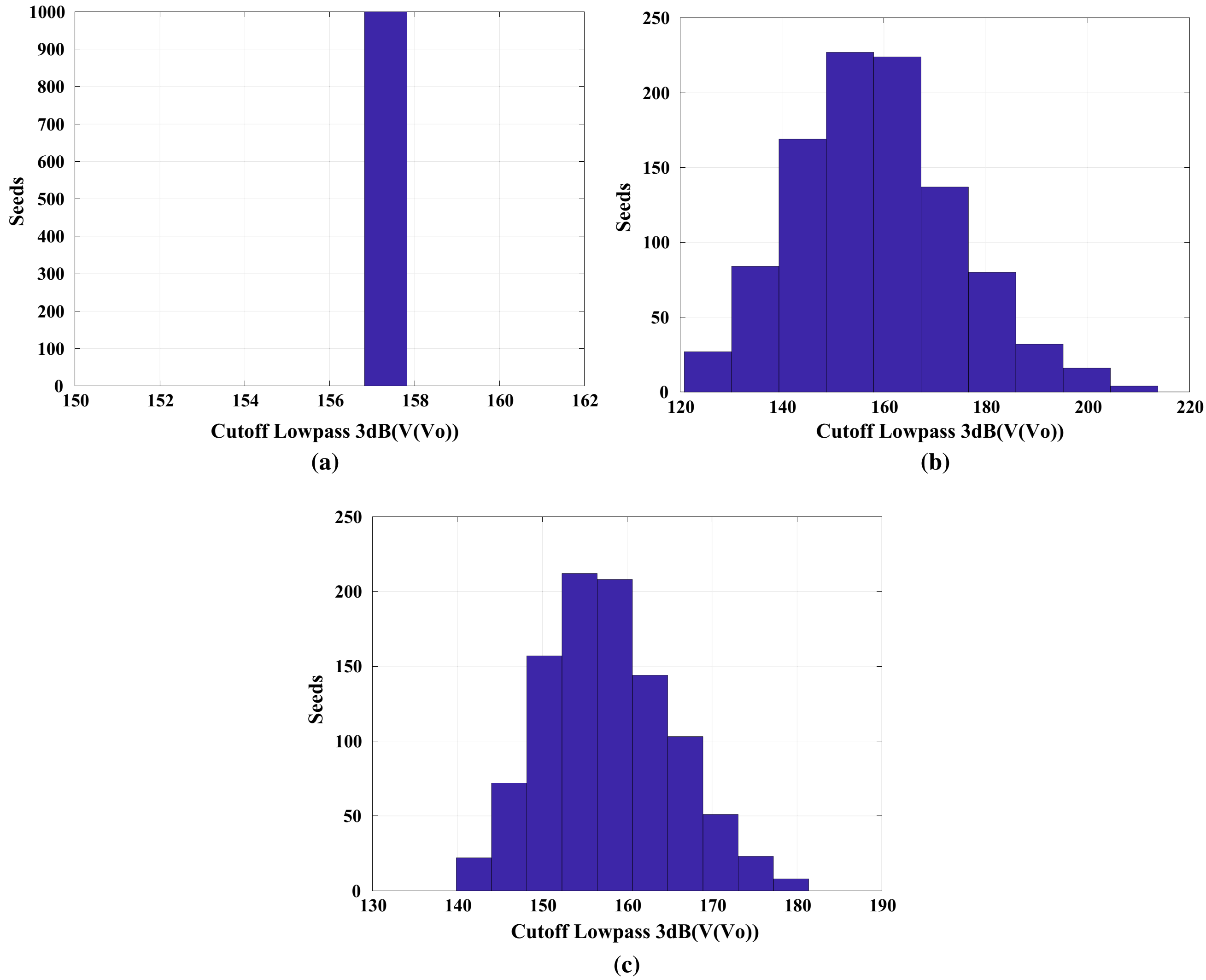


Fig. 26 Monte Carlo results histogram for PMG filter family: **a** no tolerance, **b** $TOL = 10\%$ for R_5, **c** $TOL = 10\%$ for R_7

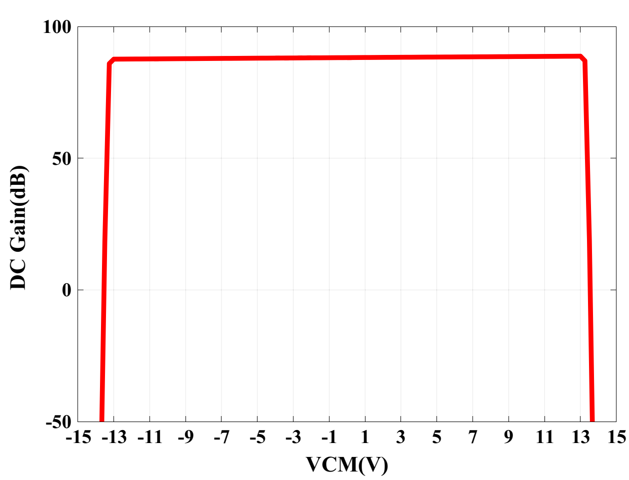


Fig. 27 TL084 DC Gain Over Sweep of the Input Common Mode

of judging factors to compare among different filter realizations. As mentioned in [52], ”It is not possible to recommend particular types of inductorless filters, many of which have not yet been proved in actual practice. The choice, of course, will depend upon the application”. Although it is around 50 years since this statement was given, it is still valid. There are no absolute good or bad filters regarding the other filters as there is always this trade-off between performance and power consumption. This work presents some detailed tables to facilitate the choice decision depending on comparing the filters from different aspects, mainly passive sensitivity. Furthermore, choosing the best filter always depends on the application, design conditions, design scheme, and available kit and hardware, which will always be the designer's responsibility.

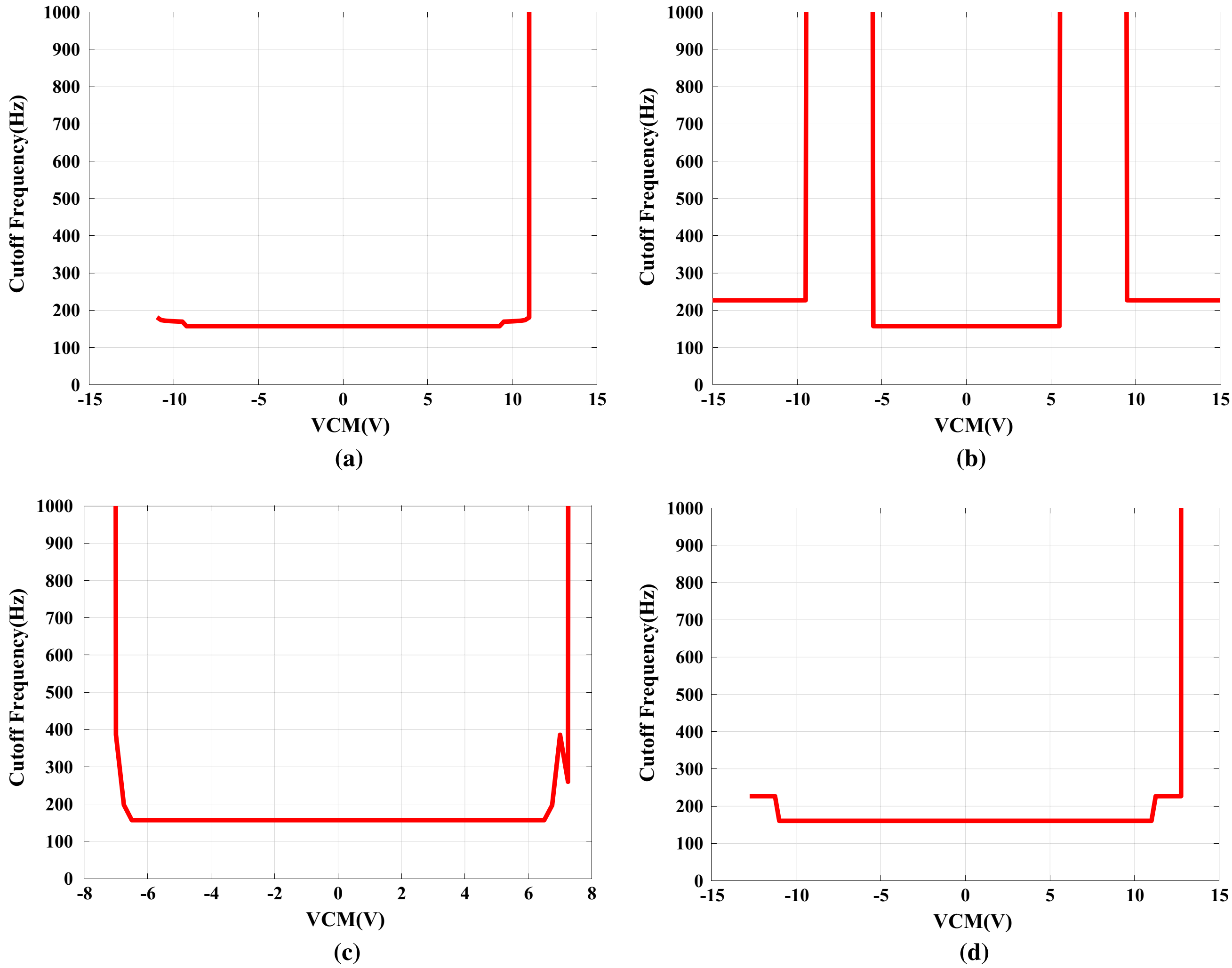


Fig. 28 Cutoff Frequency Active Sensitivity of some of the Filter Families: **a** AM, **b** BH, **c** Fliege and, **d** MB

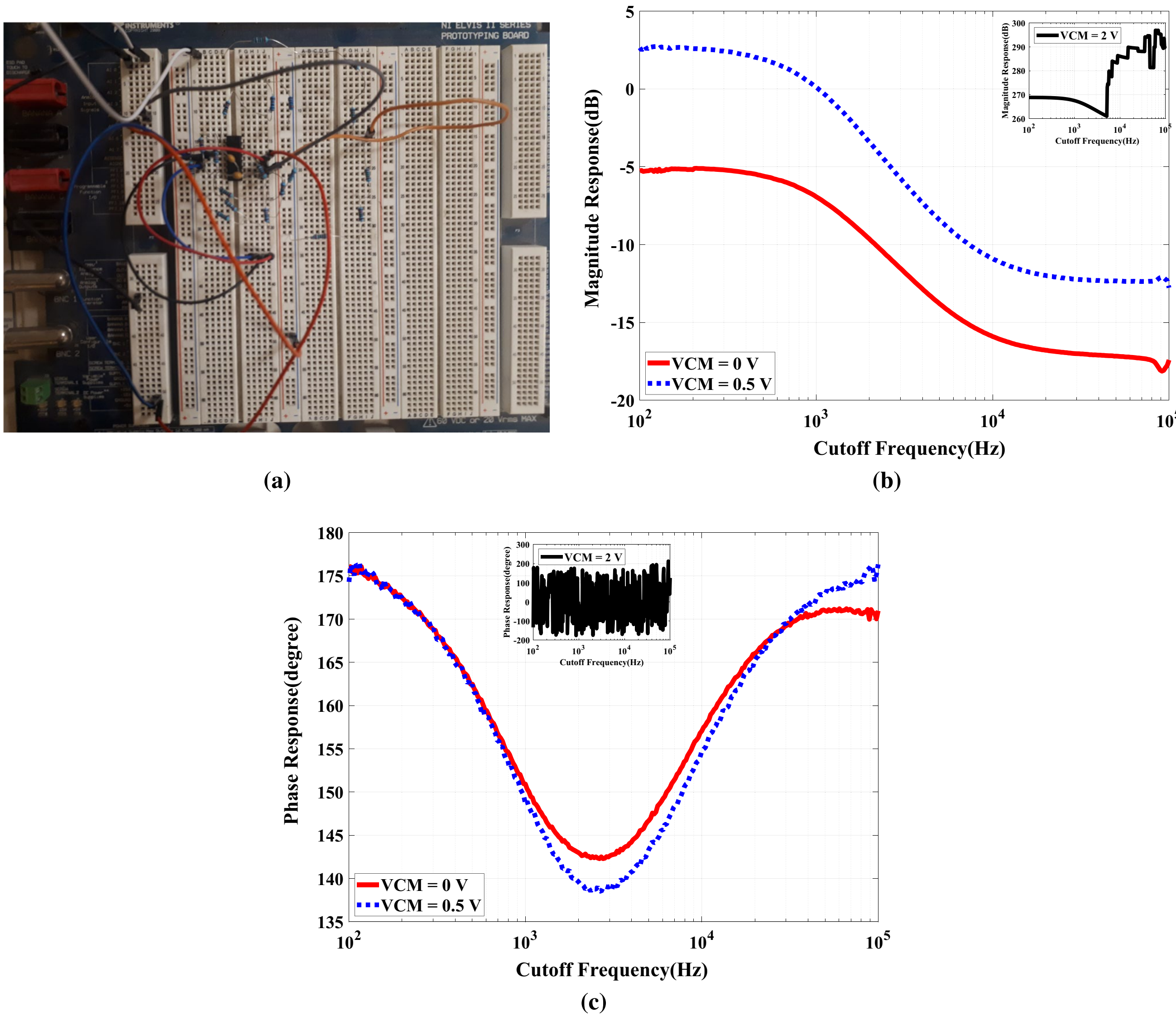


Fig. 29 MB LPF Experimental: **a** Setup, **b** Magnitude Response and, **c** Phase Response

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Data availibility There is no data associated with this manuscript.

Declarations

Conflict of interest The authors declare no competing interests.

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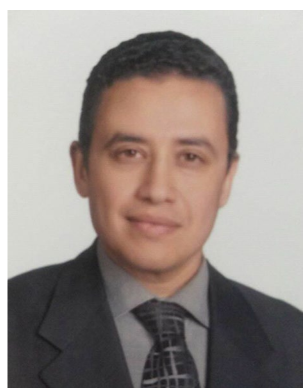

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