Design of a Combined Filter to Reduce the Attenuation Decline in Magnitude Response

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Abstract: - Certain biquad filters structures are characterized by a reduction of the attenuation at higher frequencies, caused by the finite value of the output resistance of the operational amplifier. In this paper, the design of the combined BP filter without the described decreasing is discussed for which one possible solution is to replace one of the biquads with another biquad that does not have this property. The result is a combined filter from different structures. The methodology to design a combined BP filter without the described decreasing is described in detail with the parameters of such biquads. The results of the proposed numerical procedure are verified by computer simulation, for this purpose a SPICE-like program MC-10 is used.

Key-Words: - Biquad, band pass filter, structure SK, structure H, higher order filter, magnitude response

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1 Introduction

The band-pass active RC (ARC) filters of certain structures, for example, the multi-feedback Huelsman structure (H), [1], [2], [3], [4], and more others, are based on the biquad polynomial. the structure's frequency response, namely the decline in the attenuation at higher frequencies is shown in Figure 1. After its transient frequency, for the operational amplifier can only be considered two main circuit elements: input Ri and output Ro resistance alternatively, input gi and output go admittance. Generally, this challenge also exists in relation to the band-pass type Delyiannis filter, [4].

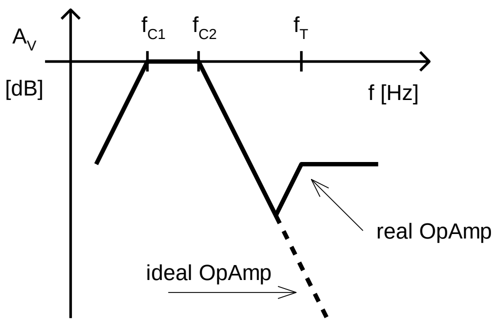

Fig. 1: The decline in the attenuation in magnitude response for the BP filter

Figure 2 depicts the cause for the band pass (BP) filter. Specifically, the top part of Figure 2 illustrates a band pass ARC biquad multi-feedback structure H. At the highest frequencies, all capacitors behave like a short circuit and the operational amplifier loses the open loop gain *A*, [5]. The reason for the above described decline is a capacitor C. For that zero impedance connects to the highest frequency when the amplification factor of operational amplifier A is already reduced to zero, for both input and output, as shown in the equivalent circuit in Figure 2.

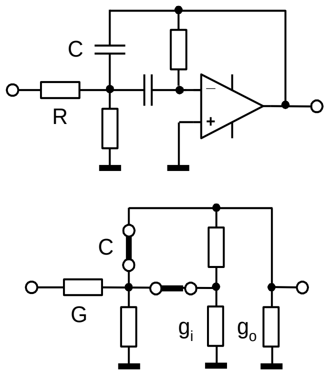

Fig. 2: Capacitors C zero impedance is the reason for the decline of the magnitude characteristic

In this case, the circuit is only a voltage divider. However, the magnitude of the voltage transfer ratio at the highest frequencies must be not equal to zero. Thus, this characteristic deviates from the characteristic of an ideal filter.

2 Problem Solution

A proposed solution to the above described problem is a combined filter, which can be designed in several ways. For example, one potential solution is the recalculation of part of the filter (i.e. recalculation of the circuit parameters of one biquad of the same structure to another biquad structure). A second approach is to combine filter design, which consists of several filter structures (biquads) in partial filter part (biquad) direct design (i.e. without recalculation of the circuit parameters). This article describes a novel design procedure in Section 3.

3 Combined Filter Design

This section describes the design procedure for the BP combined filter. The BP filter can be implemented as a BP filter and/or as an HP+LP filter, the selection criteria are formalized in (1), [3], [4].

$$\frac{f_{MAX}}{f_{MIN}} \begin{cases} < 2 & BP \\ \geq 2 & HP + LP \end{cases} \tag{1}$$

However, In the case of an even-order biquad of narrow-band band-pass filters, BP-H exhibits a decreased attenuation of the transition frequency of the operational amplifier at high frequencies, i.e. frequencies in the leaky proof zone, which again degenerates the properties of this filter. This decrease in attenuation of transit frequency exhibits not only the three well-known structures of BP-H, [6], [7], two of which are shown by Figure 3.

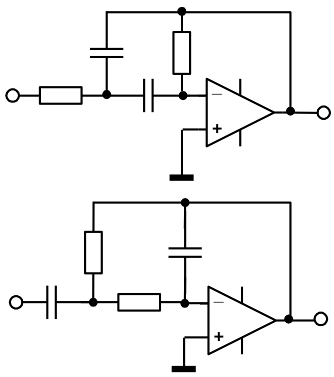

Fig. 3: The other two BP-H filter variants.

Consider an active RC band-pass filter with an operational amplifier and Butterworth approximation function for the center passband frequency $f_C = 10.10^3$ Hz, for the passband $\Delta f = 10^3$ Hz the attenuation is $A_C = 3$ dB. For stopband B = 4.10^3 Hz, the stopband attenuation is $A_S = 20$ dB. The filter calculation steps are as follows, [8], [9].

1) Described filter specification: is shown in Figure 4.

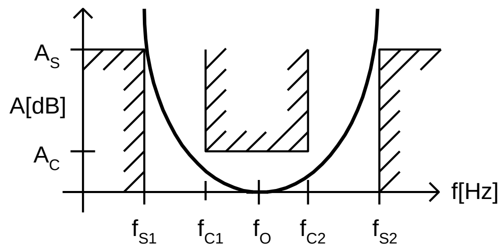

Fig. 4: Filter specification

2) Both stop frequencies are calculated as:

$$f_{S1,2} = \sqrt{f_0^2 - (\frac{B}{2})^2} \pm \frac{B}{2} = \tag{2}$$

$$= \sqrt{(10 \cdot 10^3)^2 + (\frac{4 \cdot 10^3}{2})^2} \pm \frac{4.10^3}{2} = \begin{cases} 12198\text{Hz} \\ 8198\text{Hz} \end{cases}$$

3) The following are normalized stop frequencies:

$$F_{S1} = \frac{\left|f_{S1}^2 - f_0^2\right|}{f_{S1} \cdot \Delta f} = \frac{\left|12198^2 - 10000^2\right|}{12198 \cdot 10^3} = 4{,}00 \tag{3}$$

$$F_{S2} = \frac{\left|f_{S2}^2 - f_0^2\right|}{f_{S2} \cdot \Delta f} = \frac{\left|8198^2 - 10000^2\right|}{8198 \cdot 10^3} = 4{,}00 \tag{4}$$

4) Therefore the Coefficient for stop frequency is:

$$k = \min(F_{S1}; F_{S2}) = \min(4{,}00; \quad 4{,}00) = 4{,}00 \tag{5}$$

3) Coefficient of damping: d is given by

$$d = \frac{10^{0,1 \cdot A_S} - 1}{10^{0,1 \cdot A_C} - 1} = \frac{10^{0,1 \cdot 20} - 1}{10^{0,1 \cdot 3} - 1} = 100 \tag{6}$$

4) Order of filter: n is given by (7)

$$n \geq \frac{\log d}{2 \cdot \log k} = \frac{\log 100}{2 \cdot \log 4} = 1{,}66 \tag{7}$$

Thus must be:

$$n = 2 \tag{8}$$

5) Coefficient of the wide band: k is given by (9):

$$f_{C1,2} = \sqrt{f_0^2 - (\frac{\Delta f}{2})^2} \pm \frac{\Delta f}{2} = \tag{9}$$

$$= \sqrt{(10.10^3)^2 + (\frac{10^3}{2})^2} \pm \frac{10^3}{2} = \begin{cases} 10512 \quad \text{Hz} \\ 9512 \quad \text{Hz} \end{cases}$$

thus:

$$k = \frac{f_{C2}}{f_{C1}} = \frac{10512}{9512} = 1{,}105 < 2 \tag{10}$$

5) The Butterworth approximation coefficients, [10], [11], are presented in Table 1.

Table 1. Butterworth Approximation Coefficients

N	F_O	Q
2	1	0,7071

6) Coefficient α is given by (11):

$$\alpha = \frac{2 \cdot f_0}{F_0 \cdot \Delta f} = \frac{2 \cdot 10 \cdot 10^3}{2 \cdot 10^3} = 20 \quad (11)$$

7) Quality factor of sections $\tilde{Q}$:

$$Q = \frac{\tilde{Q}}{\sqrt{2}} \cdot \sqrt{1 + \alpha^2 + \sqrt{(1+\alpha^2)^2 - (\frac{\alpha}{\tilde{Q}})^2}} = \quad (12)$$

$$= \frac{0,7071}{\sqrt{2}} \cdot \sqrt{1 + 20^2 + \sqrt{(1+20^2)^2 - (\frac{20}{0,7071})^2}} =$$

$$= 14,15$$

8) Coefficient k_F:

$$k_F = \frac{Q}{\alpha \cdot \tilde{Q}} + \sqrt{(\frac{Q}{\alpha \cdot \tilde{Q}})^2 - 1} = \quad (13)$$

$$= \frac{14,15}{20 \cdot 0,7071} + \sqrt{(\frac{14,15}{20 \cdot 0,7071})^2 - 1} = 1,036$$

9) The passband gain of the partial filters

$$A_0 = \sqrt{Q \cdot (k_F - \frac{1}{k_F}) + 1} = \quad (14)$$

$$= \sqrt{14,15 \cdot (1,036 - \frac{1}{1,036}) + 1} = 1,416$$

10) The middle frequencies for partial filters are

$$f_{01} = \frac{f_0}{k_F} = \frac{10^4}{1,036} = 9653 \quad \text{Hz} \quad (15)$$

$$f_{02} = f_0 \cdot k_F = 1,036 \cdot 10^4 = 10360 \quad \text{Hz} \quad (16)$$

11) Capacity is determined by (17)

$$C = \frac{10^{-7}}{\sqrt{f_C}} = \frac{10^{-7}}{\sqrt{10^4}} = 10^{-9}\,\text{F} \quad (17)$$

and/or can be chosen, for example as

$$C = 10 \cdot 10^{-9}\,\text{F} \quad (18)$$

12) Resistors must be calculated in following order R_{13}, R_{11}, R_{12}, the value for 1st section are:

$$R_{13} = \frac{Q}{\pi \cdot f_{01} \cdot C} = \frac{14,15}{\pi \cdot 9653 \cdot 10 \cdot 10^{-9}} = 46,70 \cdot 10^3\,\Omega \quad (19)$$

$$R_{11} = \frac{Q}{2 \cdot \pi \cdot f_{01} \cdot C \cdot A_0} = \quad (20)$$

$$= \frac{14,15}{2 \cdot \pi \cdot 9653 \cdot 10 \cdot 10^{-9} \cdot 1,1416} = 16,50 \cdot 10^3\,\Omega$$

$$R_{12} = \frac{Q}{(2 \cdot Q^2 - A_0) \cdot \pi \cdot f_{01} \cdot C} = \quad (21)$$

$$= \frac{14,15}{(2 \cdot 14,15^2 - 1,416) \cdot \pi \cdot 9653 \cdot 10 \cdot 10^{-9}} = 58,1\Omega$$

and for 2nd section:

$$R_{23} = \frac{Q}{\pi \cdot f_{02} \cdot C} = \frac{14,15}{\pi \cdot 10360 \cdot 10 \cdot 10^{-9}} = 43,50 \cdot 10^3\,\Omega \quad (22)$$

$$R_{21} = \frac{Q}{2 \cdot \pi \cdot f_{02} \cdot C \cdot A_0} = \frac{14,15}{2 \cdot \pi \cdot 10360 \cdot 10 \cdot 10^{-9} \cdot 1,1416} =$$

$$= 15,40 \cdot 10^3\,\Omega \quad (23)$$

$$R_{22} = \frac{Q}{(2 \cdot Q^2 - A_0) \cdot \pi \cdot f_{02} \cdot C} = \quad (24)$$

$$= \frac{14,15}{(2 \cdot 14,15^2 - 1,416) \cdot \pi \cdot 10360 \cdot 10 \cdot 10^{-9}} = 54,2\Omega$$

13) Circuit diagram of the designed filter is in Figure 5.

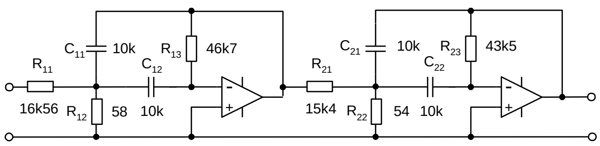

Fig. 5: Designed circuit

14) It is required to use an operational amplifier, whose transient frequency f_T is given as (25):

$$f_T \geq 200 \cdot f_O \cdot Q \quad (25)$$

where Q is the quality. Thus must be:

$$f_T \geq 200 \cdot f_O \cdot Q = 200 \cdot 10 \cdot 10^3 \cdot 14,15 = 2,8 \cdot 10^7\,\text{Hz} \quad (26)$$

That means it is necessary to choose

$$f_T \geq 28\text{MHz} \quad (27)$$

Therefore an operational amplifier LF 400 C is used for example.

15) Simulation of calculated results.

First, the spice-like program MC-10 was used for the simulation of calculated results. The real operational amplifier LF 400 C is used with the following parameters Ao=200 K, GBW = 18 MEG, and ROUT = 50 Ω. The simulation of the calculated results by the MC-10 program is shown in Figure 6.

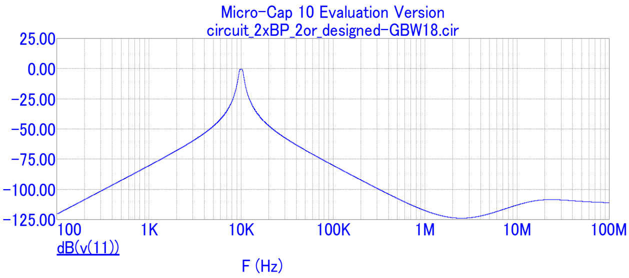

Fig. 6: Simulation results if Op.Amp. LF400C, GBW 18 MHz is used.

In another case, if the equation $f_T \geq 200 \cdot f_O \cdot Q$ is not considered for the design, then there will be a frequency shift. In this case, the simulation of the results of Op. Amp with GBW 1 MHz is used are depicted in Figure 7, whereas, the detail around the center frequency of 10 kHz is in Figure 8.

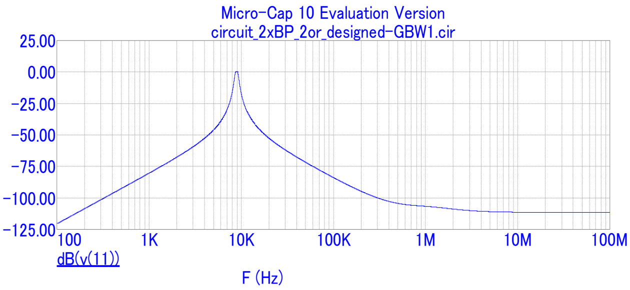

Fig. 7: Frequency shift if Op.amp.: LM 741, GBW 1 MHz is used

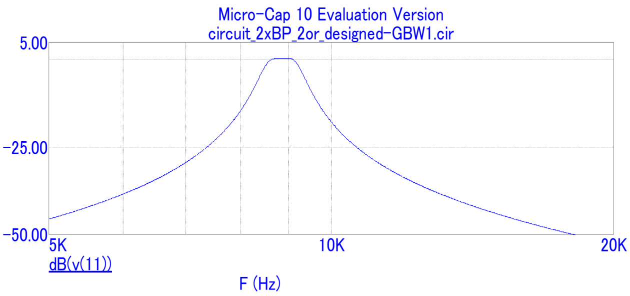

Fig. 8: Frequency shift in detail from Figure 7 if Op.Amp. LM741, GBW 1 MHz is used.

16) Correction of the attenuation decline at high frequencies.

As we can see from Figure 6, the attenuation does not decrease at high frequencies, it stabilizes at a constant value. This disadvantage has not on the contrary BP-SK with a grounded capacitor at the input. Its inclusion in the cascade can then suppress this disadvantage.

17) Calculation of SK-BP biquad

The first section with BP-H will be changed by the BP-SK filter.

Capacity is determined by (28)

$$C = \frac{10^{-7}}{\sqrt{f_C}} = \frac{10^{-7}}{\sqrt{10^4}} = 10^{-9}\,F \qquad (28)$$

and/or can be chosen, for example as $C = 10 \cdot 10^{-9}\,F$.

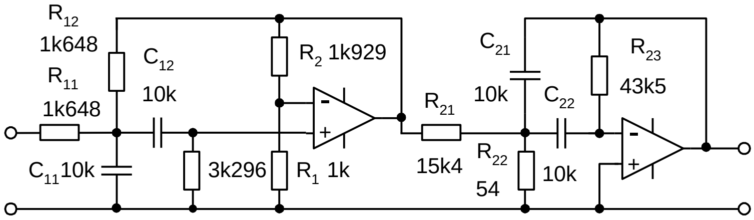

Fig. 9: Circuit diagram of combined recalculated SK-H BP filter.

18) The resistor R is given by

$$R = \frac{1}{2\cdot\pi\cdot f_{01}\cdot C} = \frac{1}{2\cdot\pi\cdot 9653\cdot 10\cdot 10^{-9}} = 1648\Omega \quad (29)$$

19) Resistors for amplifier feedback to amplify adjust are given by:

$$R_2 = \frac{2\cdot Q-1}{Q} = \frac{2\cdot 14{,}15-1}{14{,}15} = 1929 \quad \Omega \quad (30)$$

$$R_1 = \frac{R_2}{2-\frac{1}{Q}} = \frac{1929}{2-\frac{1}{14{,}15}} = 1000 \quad \Omega \quad (31)$$

20) Circuit diagram of combined SK-H BP filter
The circuit diagram of the combined SK-H BP filter is shown in Figure 9.

4 Simulation Results

The results of the proposed numerical procedure are verified by computer simulation, [12], [13]. Next for the simulation of calculated results the spice-like program MC-10 was used. The operational amplifier is used LF 400 C with parameters Ao=200 K, GBW = 18 MEG, ROUT = 50 Ω, i.e. it is the real operational amplifier. Simulation of calculated results by the spice-like program MC-10 is shown in Figure 10.

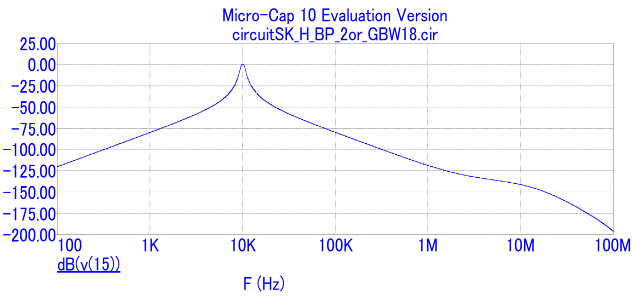

Fig. 10: Circuit magnitude characteristic after recalculation to a combined filter, Op. Amp. LF 400C, GBW 18 MHz is used

Figure 11 depicts the detail around the center frequency of 10 kHz.

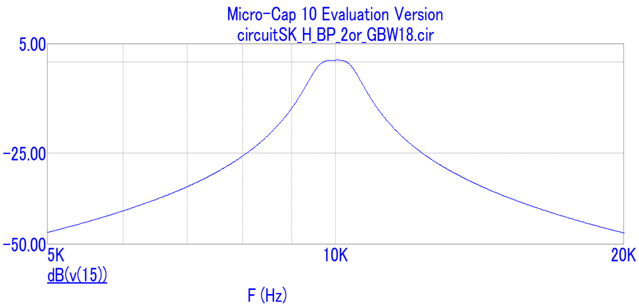

Fig. 11: Circuit magnitude characteristic from Figure 10 in detail, Op. Amp. LF 400C, GBW 18 MHz is used

5 Discussion

The magnitude and phase characteristics before and after recalculation are shown in Figure 6 and Figure 10. As is depicted, the phase characteristics in Figure 12 and Figure 13 are identical, only the phase is decreased by 180° due to connection of a noninverting operational amplifier in the H-filter structure, as we can see. The phase is increased by 180° due to the use of a noninverting operational amplifier connection. If this is a problem, it can be easily eliminated by including another inverting amplifier as a voltage follower in the cascade.

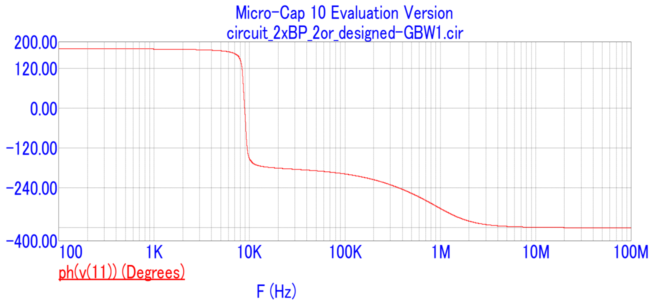

Fig. 12: Circuit phase characteristic

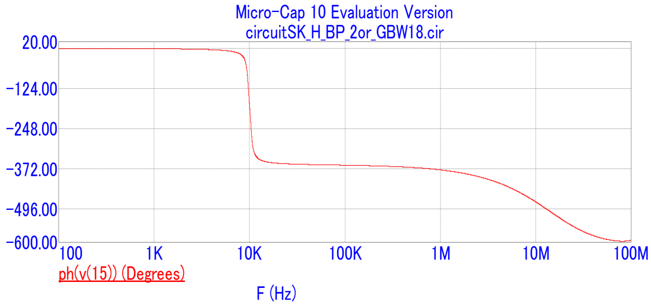

Fig. 13: Circuit phase characteristic after recalculation to a combined filter.

Another design procedure with recalculation of one biquad is described in [14], for the LP filter.

6 Conclusion

In many cases, the Huelsmann structure is a very popular filter structure due to the achievement of high-quality Q. The disadvantage of the band-pass filter of the Huelsmann structure, i.e. the decrease of the attenuation above the transient frequency of the operational amplifier, is discussed. Here, A new filter structure is proposed to eliminate this disadvantage. In the first step, the general filter structure must be designed. If the filter structure will be chosen first, the design steps 19, 20, and 21 can be omitted. The results of the simulations show a monotonic decrease in the amplitude characteristic, without a decrease in the attenuation.

This new design combined filter procedure is described for band-pass structure only, but it can be used for other filter structures as well.

Based on up-to-date published research projects, a filter assembled from biquads of the same structure was designed, and then one biquad was selected and recalculated to another more suitable type. The contribution of this research work is the proposal of a procedure for the direct design of a combined filter, when biquads of different structures are directly designed, i.e. without the need for subsequent conversion of one type of biquad to another type.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The author contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest

The author has no conflict of interest to declare.