SYNTHESIS OF UNIVERSAL FILTERS

Lubomír Frőhlich

Doctoral Degree Programme (3), FEEC BUT

E-mail: xfrohl00@stud.feec.vutbr.cz

Supervised by: Jiří Sedláček

E-mail: sedlacj@feec.vutbr.cz

Abstract: The article describes qualities of less known universal filters, which contain 3 and more operational amplifiers, and compares these filters with circuits Akerberg – Mossberg or Kerwin – Huelsman – Newcomb, which can be applied in ARC oscillators or retuning STC circuits. Apart from derivation of the transferable function of these filters for individual outputs, we can also solve possibilities of a complete design and using of digital operating of individual parameters and their usage in some circuits in practice.

Keywords: Universal, transfer function, tuning

1. INTRODUCTION

There are many kinds of universal ARC filters and in most cases these can realize transfer function H(s) in biquad form (1).

$$H(s) = K\frac{N(s)}{D(s)} = K\frac{b_2 s^2 + b_1 s + b_0}{a_2 s^2 + a_1 s + a_0} = K\frac{s^2 + s\omega_z/Q_z + \omega_z^2}{s^2 + s\omega_0/Q_0 + \omega_0^2} \tag{1}$$

One of the most used universal circuits in practice is Akerberg – Mossberg, Kerwin – Huelsman – Newcomb or Towa – Thomas. The first two listed filters enable current realization of filters of type low-pass (LP), high-pass (HP), band-reject (BR), band-pass (BP), but also low-pass or high-pass notch (LPN/HPN) and all-pass (AP). The tuning for these filters is realized by parallel change of elements $R_1 - R_2$ a $C_1 - C_2$. Both filters are characterized by an independent setting of individual parameters and by usage of the band up to 10MHz. Below stated filters and their qualities will be mainly compared with these filters, which already found their usage in practice.

2. THE SYNTHESIS OF UNIVERSAL FILTERS

On the figure 1, there is a connection of a universal filter, which contain 4 operational amplifiers (OA) and enables to realize following transfer functions of type DPN, HPN, PZ, DP, HP a PP. Possibilities of tuning or retuning can be also realized with the help of condensers C_A a C_B or resistors R_1 a R_2 where we have to consider dependence on Q-factor, by a change of the resistor R_Q.

For derivation of transfer characteristics for individual outputs in OA in a circuit, we used SNAP program, which is able to display function for a required output. A modified function for OA U1 can be seen in the following formula (2):

$$H(s) = \frac{N(s)}{D(s)} = \frac{-R_2 R_3 R_4 R_5 R_C R_E - s(R_1 R_2 R_5 R_A R_C R_D R_E C_A) - s^2(R_1 R_2 R_3 R_4 R_A R_B R_C R_E C_A C_B)}{+R_1 R_3 R_4 R_5 R_C R_E + s(R_1 R_2 R_4 R_5 R_A R_C R_D C_A) + s^2(R_1 R_2 R_3 R_4 R_5 R_A R_B R_E C_A C_B)} \tag{2}$$

For a modification of the function (2), it is necessary to choose suitable initial circuit conditions, which can be the following ones: $R_a = R_b = R_c = R_d = R_e = R$, $C_a = C_b = C_{lad}$, $R_1 = R_2 = R_{dig}$, $R_3 = R_Q$.
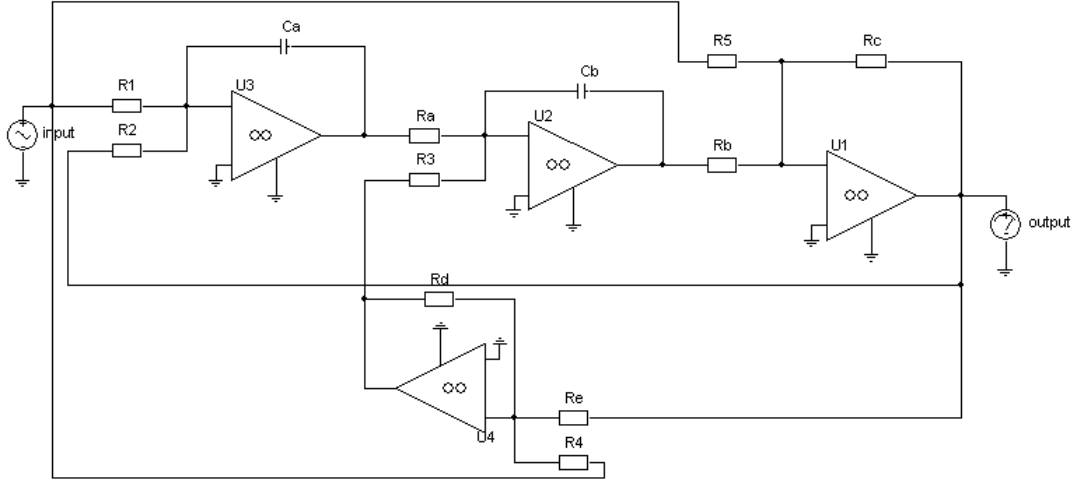
Figure 1: An illustration of the universal filter with 4OA [1].

In a modified transfer function (3), R_{dig} is equal to R_1, R_2 and C_{lad} is equal to C_A, C_B, these elements enable fine or coarse tuning of a frequency circuit:

$$H(s) = \frac{N(s)}{D(s)} = -\frac{R_C}{R_5} \frac{s^2 + s\dfrac{R_5 R_D}{R_3 R_4 R_B C_B} + \dfrac{R_5}{R_1 R_A R_B C_A C_B}}{s^2 + s\dfrac{R_C R_D}{R_3 R_B R_E C_B} + \dfrac{R_C}{R_2 R_A R_B C_A C_B}} = -\frac{R}{R_5} \frac{s^2 + s\dfrac{R_5}{R_Q R_4 C_{lad}} + \dfrac{R_5}{R_{dig} R^2 C_{lad}^2}}{s^2 + s\dfrac{1}{R_Q C_{lad}} + \dfrac{1}{R_{dig} R C_{lad}^2}} \quad (3)$$

From denominator of the function D(s) (3), we can derive relations for a frequency f_0 and Q-factor (4) and (5):

$$f_0 = \frac{1}{2\pi} \frac{1}{C_{lad}} \sqrt{\frac{1}{R_{dig} R}} \quad (4)$$

$$Q_0 = R_Q \sqrt{\frac{1}{R_{dig} R}} \quad (5)$$

From the figure (5), we can see dependence of setting of Q-factor by a rezistor R_Q on the resistors R_1 and R_2, which serve for a fine setting of a circuit frequency.

From numerator of the function N(s) (3) for an output of operational amplifier U1 at initial conditions $R_a = R_b = R_c = R_d = R_e = R$, $C_a = C_b = C_{lad}$, $R_1 = R_2 = R_{dig}$, $R_4 = \infty$, $R_3 = R_Q$ is accepted relation for LPN, HPN and BR (6):

$$N(s) = -\frac{R}{R_5}\left(s^2 + s\frac{R_5}{R_3 R_4 C} + \frac{R_5}{R_{dig} R C^2} \right) = -\frac{R}{R_5}\left(s^2 + \frac{R_5}{R} \frac{1}{R_{dig} R C_{lad}^2} \right) \quad (6)$$

For frequency notch of transfer f_N is accepted relation $R_5 = (R.f_n^2)/f_0^2$.

For transfer of OA U2 it is possible to create transfer function of type LP (7) and BP (8) at initial conditions for LP: $R_4 = R_5$ and for BP: $R_a = R_b = R_c = R_d = R_e = R_5 = R$.

$$N(s) = \frac{R_2 R_3 R_4 R_B R_E (R_5 - R_C)}{R_1 R_2 R_3 R_4 R_5 R_A R_B R_E C_A C_B} + s\frac{R_1 R_2 R_A R_B R_D C_A R (R_5 - R_4)}{R_1 R_2 R_3 R_4 R_5 R_A R_B R_E C_A C_B} = \frac{(R_5 - R)}{R_5} \frac{1}{R_{dig} R C_{lad}^2} \quad (7)$$

$$N(s) = \frac{R - R_4}{R_4} s \frac{1}{R_Q C_{lad}} \tag{8}$$

On the output of operational amplifier U3 it is possible to gain LP and BP. However, there is a problem with the fulfilling of the basic conditions from the relations (4) and (5). Because of these reasons, it is not possible to use these transfer functions.

On the output of the last OA, or U4 after a derivation, we obtain functions for HP (9), LP (10) a BR (11), under conditions for HP: $R_4 = R$ for LP: $R_4 = R_5 = R_{45}$ and for BR: $R_5 = R$.

$$N(s) = -s^2 \frac{(R_5 - R_4)}{R_5} = -\frac{(R_5 - R)}{R_5} s^2 \tag{9}$$

$$N(s) = \frac{(R_4 - R)}{R_4} \left(\frac{1}{R_{dig} R C_{lad}^2} \right) \tag{10}$$

$$N(s) = \frac{(R_4 - R)}{R_4} \left(\frac{1}{R_{dig} R C_{lad}^2} + s^2 \right) \tag{11}$$

Out of above mentioned relations, it is possible to design complex values for individual components and with the help of SPICE program we can verify the function of the entire filter. Some examples of simulation are stated on the figures 2 to 5. One of the disadvantage of this circuit is a big scatter of a value of the resistor R_5 for transfer functions LPN, HPN a BR. This resistor decides about a given function and his value lies at intervals from several Ω up to MΩ. Another inconvenient factor can be also scatter of resistors R_{dig}, which we need as smallest as possible for tuning with the help of digital potentiometers, regarding usage of circuits for the biggest possible frequency. Thus, for a design $R_{dig\,max} = 1k\Omega$ we obtain unrealized $R_{dig\,min} = 10\Omega$.
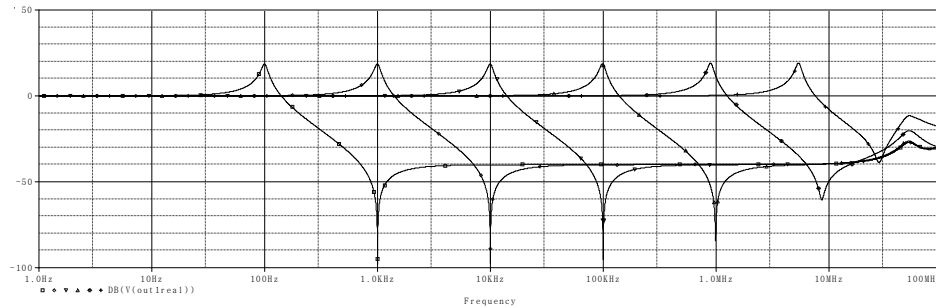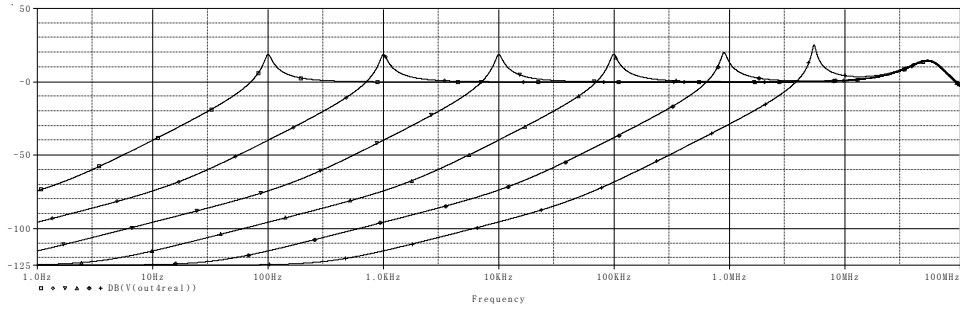

Figure 2:   Simulation of LPN output U1_CLC440/CL, Q = 10.
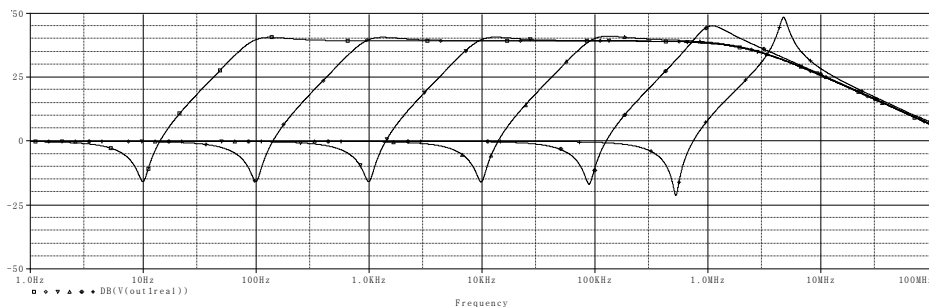
Figure 3:   Simulation of HPN output U1_CLC440/CL, Q = 1.
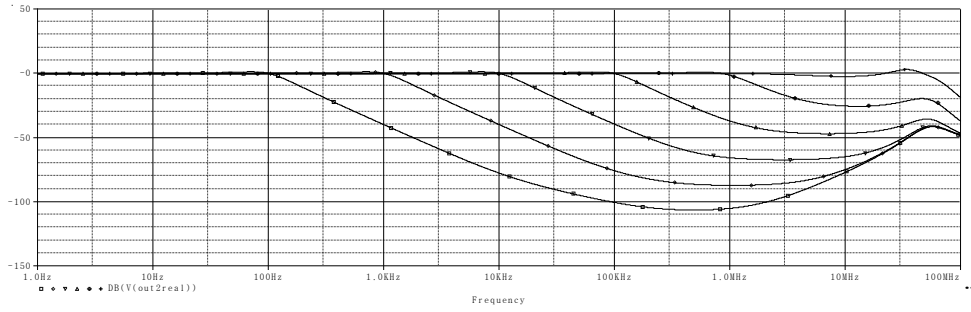
**Figure 4:**   Simulation of LP output U2_CLC440/CL, Q = 1.

Figure 5:   Simulation of HP output U4_CLC440/CL, Q = 10.

According to stated simulations, this circuit can be used maximally up to 1MHz. On higher frequencies, there is a significant characteristic deformation.

2.1.   OTHER TYPES OF THE FILTERS

The examples of other universal filters are on the figures 6-7. At these circuits, there is not stated a complex synthesis of a circuits, but only a brief description of the circuit. The circuit on the figure 6 is able to realize transfer functions of type LPN, HPN and BR on the output of operational amplifier U1, on the output of OA U2 is gaining LP and BR and for the output of U3 we have HP or BP. In the same way as at the above mentioned circuit, the tuning of a frequency f_0 with the help of resistor dependent on a Q-factor and another disadvantage is a relation C_3/C_{lad} for setting of a frequency of a transfer notch. The initial conditions are $R_a = R_b = R_2 = R$, $C_1 = C_2 = C_{lad}$, $R_1 = R_3 = R_{dig}$, $R_c = R_Q$.
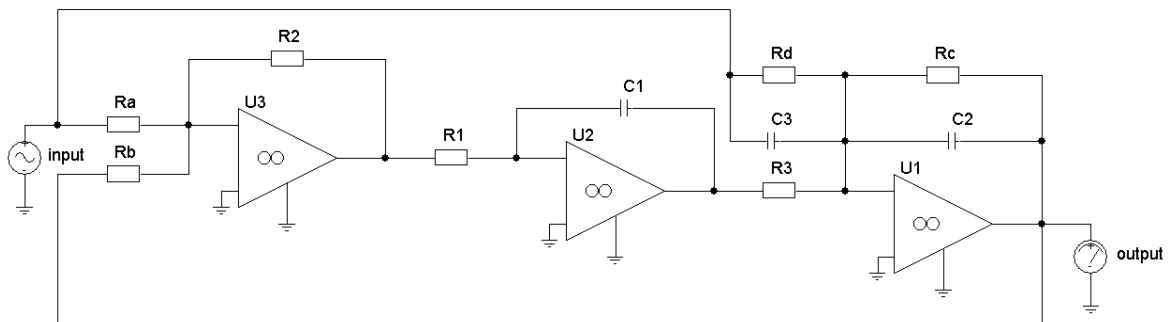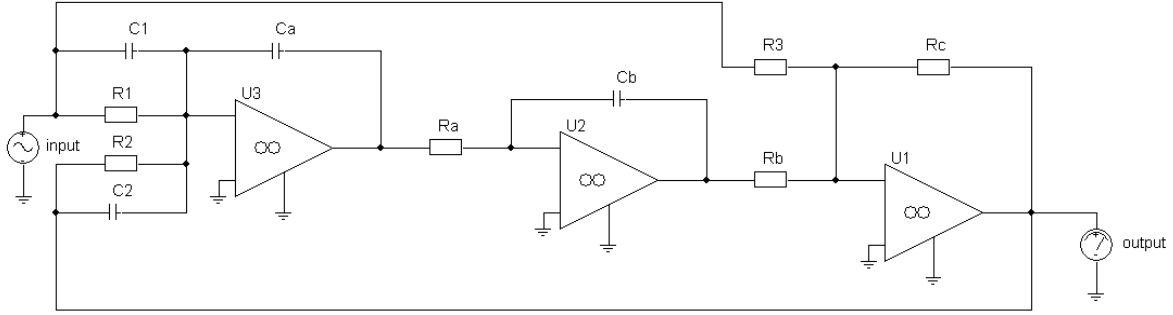

Figure 6:   Example of universal filter with 3OA [1].

The transfer function for this circuit is the following (11).

$$H(s) = \frac{N(s)}{D(s)} = -\frac{C_3}{C_2} \frac{s^2 + s\dfrac{1}{C_3 R_D} + \dfrac{R_2}{C_3 R_1 R_3 C_1 R_A}}{s^2 + s\dfrac{1}{C_2 R_C} + \dfrac{R_2}{C_2 R_1 R_3 C_1 R_B}} = -\frac{C_3}{C_{lad}} \frac{s^2 + s\dfrac{1}{C_3 R_D} + \dfrac{1}{C_3 R_{dig}^2 C_{lad}}}{s^2 + s\dfrac{1}{C_{lad} R_Q} + \dfrac{1}{R_{dig}^2 C_{lad}^2}} \quad (11)$$

The circuit on the figure 7 is able to realize on the output U1 LPN, HPN and BR on other outputs we can obtain function of type LP, BP and for U3 only HP. For operating of the filter with the help of $C_a = C_b = C_{lad}$ a $R_1 = R_2 = R_{dig}$ it is necessary to consider retuning of a capacitor $C_2 = C_q$. The transfer function is obvious in the following figure (12).

Figure 7:   An example of universal filter with 3OA [1].

$$H(s) = \frac{N(s)}{D(s)} = -\frac{R}{R_3} \frac{s^2 + s\left(\dfrac{C_1 R_3}{C_A C_B R_A R_B}\right) + \dfrac{R_3}{R_1 C_A C_B R_A R_B}}{s^2 + s\left(\dfrac{C_2}{C_A C_B R_A}\right) + \dfrac{1}{R_2 C_A C_B R_A}} = -\frac{R}{R_3} \frac{s^2 + s\left(\dfrac{C_1 R_3}{C_{lad}^2 R^2}\right) + \dfrac{R_3}{R_{dig} C_{lad}^2 R^2}}{s^2 + s\left(\dfrac{C_2}{C_{lad}^2 R}\right) + \dfrac{1}{R_{dig} C_{lad}^2 R}} \quad (12)$$

3. CONCLUSION

In the article, there are less known examples of the universal filters, for which we made a complete analysis with the help of SNAP and the following simulations in SPICE program. At the stated filters, it is possible to tune the frequency for decades with the help of capacitors C_{lad}. Fine-tuning with the of resistors R_{dig} is not possible due to the dependence on the Q-factor. The next problem is a very difficult creating of transfer functions, which cannot be used constantly also for example at Akerberg-Mossberg circuit, but set the circuit according to the initial conditions. Afterwards, it is possible to gain stated transfer functions. The next problematic issues can be also considered for instance a spread of value of a building elements and setting of frequency notch transfer with the help of the rate of two capacitors. The circuits were simulated with OA CLC 440/CL and the maximal reached frequency with the deformation of the transfer function approximately 1MHz and Q-factor Q=10.

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