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Second-Order Filters with Independent Setting and Adjustment of Basic Parameters

Antypenko R. V., Kyrpatenko I. M., Movchanyuk A. V., Fesich W. P.

National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine

E-mail: *ikirpatenko@ukr.net*

A new topology of the second-order low-pass filter containing three operational amplifiers is proposed. As known, a feature of second-order filters based on operational amplifiers is the interdependence of the main filter parameters, such as the pole frequency, Q factor and gain. The second-order filters synthesized by the state variable method have the smallest relationship between the main parameters, but they also do not allow independent adjustment of the gain and Q factor, and contain at least three operational amplifiers. The proposed low-pass filter topology also contains three operational amplifiers and provides the possibility of independent setting of the pole frequency, Q factor and gain, as well as the possibility of independently adjustment of the Q factor and gain. Relationships have been obtained that relate the pole frequency, Q factor and filter gain to the nominal values of the passive filter elements. On the basis of these ratios, the possibility of independently changing the Q factor and gain of the filter is shown. On the basis of this topology, a second-order universal filter was synthesized with the possibility of independent setting and adjustment of the main parameters. A cut-off filter with independent installation and adjustment of the main parameters is also offered. Examples of second-order low-pass filter calculations and simulation results are given, which confirm the correctness of the calculations. Also, the results of modeling universal and rejection filters are given.

Keywords: active filter; second-order filter; pole frequency; Q factor

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Introduction

As is known, both passive RC filters of the first order and active filters of the second and higher orders are used to filter signals in the sound and low-frequency ultrasonic range.

A second-order active RC filter, namely, a filter in which the dependence of the output signal on the input signal is described by a second-order linear differential equation, can be implemented using different topologies. Such topologies include: low-pass filter (LPF), high-pass filter (HPF), bandpass filter (BPF) of Sallen-Key topology, LPF, HPF, BPF with multi-loop feedback, LPF, HPF, BPF of biquad topology [1–4]. Salen-Key filters and multi-loop feedback filters have one operational amplifier (OA) [5], the biquad filter has three OAs. Also known a state variable filters realization which has also three OAs [6, 7].

All filters created according to the above topologies are characterized by the fact that they do not have the ability to independently set and adjust the main parameters: pole frequency ω_0, quality factor Q and amplification K [8–11]. Since the change of one parameter during adjustment causes the changes of others [12], the process of setting the main parameters of such filters and their adjustment is iterative in nature, takes a lot of time and requires the involvement of highly qualified personnel.

There are filters based on full resistance converters that contain two OAs and have the ability to independently set the main parameters when using a certain algorithm described in [1]. However, it is impossible to independently adjust the already set parameters, since the adjustment elements of each specific parameter also affect other parameters.

1 Formulation of the problem

As it was said above, the existing types of second-order filters with a minimum number of OAs do not provide independent adjustment of quality factor and amplification. Thus, the use of such filters, especially for research purposes, where the signal parameters are not precisely known in advance and the filter parameters may require multiple adjustments, is not optimal. Based on this, the task of developing filters, first of all low-pass filters, which contain a minimum number of OAs and provide independent adjustment of the quality factor and the amplification factor was set.

2 Second-order low-pass filter with independent setting and adjustment of main parameters

The article proposes a new topology of a second-order low-pass filter with three OAs, which enables independent setting of the pole frequency ω_0, quality factor Q, and amplification factor K. After setting the parameters, the topology allows for independent adjustment of the amplification factor K and quality factor Q. The scheme of the proposed LPF is shown in Fig. 1.

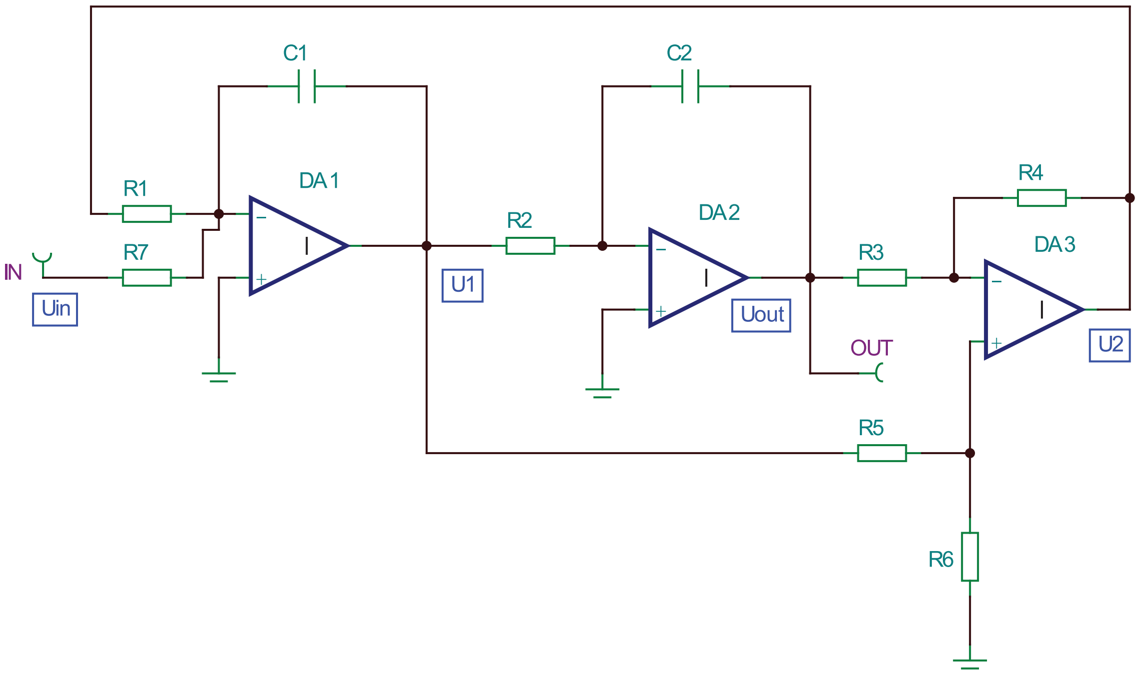


Fig. 1. Second-order low-pass filter with independent setting and adjustment of the main parameters

The system of Laplace-transformed equations for this topology is:

$$\begin{cases} U_1 = -\dfrac{U_{in}}{T_1 \cdot p} - \dfrac{U_2}{T_2 \cdot p} \\ U_{out} = -\dfrac{U_1}{T_3 \cdot p} \\ U_2 = U_1 \cdot K_1 - U_{out} \cdot K_2 \end{cases}$$

where:

$$T_1 = R7 \cdot C1, \quad T_2 = R1 \cdot C1, \quad T_3 = R2 \cdot C2,$$

$$K_1 = \frac{R6}{R5+R6} \cdot \left(1+\frac{R4}{R3}\right), \quad K_2 = \frac{R4}{R3},$$

p is the Laplace operator.

The transfer function is:

$$K_u(p) = \frac{K \cdot {\omega_0}^2}{p^2 + \frac{\omega_0}{Q} \cdot p + {\omega_0}^2},$$

$$K = \frac{T_2}{T_1 \cdot K_2} = \frac{R1}{R7 \cdot K_2} = \frac{\gamma}{K_2},$$

$$\omega_0 = \sqrt{\frac{K_2}{T_2 \cdot T_3}}, \quad Q = \frac{1}{K_1}\sqrt{K_2 \frac{T_2}{T_3}}.$$

It is advisable to apply the following filter adjustment algorithm: set the pole frequency using the time constants T_2, T_3, if necessary, adjust using the coefficient K_2. The quality factor Q value is set using the K_1 (resistors $R5$ or $R6$), the filter amplification K is set using the γ parameter (resistor $R7$). If required, the Q and amplification K can be changed independently of each other using the K_1 (resistors $R5$ or $R6$) and γ (resistors $R7$) parameters.

As an example, below is the filter synthesis procedure with the following parameters: pole frequency $f_0 = 100\,Hz$, quality factor $Q = 3$, amplification $K = 10$.

To simplify calculations, it is assumed that:

$$R1 = R2 = R, \quad C1 = C2 = C, \quad T_1 = T_2 = T, \quad K_2 = 1, \quad R3 = R4 = 10\,kOhm. \tag{1}$$

Then the pole frequency:

$$\omega_0 = 2\pi f_0 = \frac{1}{T} = \frac{1}{RC}.$$

If $C = 100\,nF$, then $R = 16\,kOhm$. To ensure $K = 10$, $R7 = 1.6\,kOhm$.

The quality factor, according to (1) is equal to:

$$Q = \frac{1}{K_1} = \frac{R5 + R6}{2 \cdot R6},$$

then

$$R6 = \frac{R5}{2Q - 1}.$$

If we take $R5 = 100\,kOhm$, then $R6 = 20\,kOhm$. The result of modeling this filter in the Tina-TI simulator is shown in Fig. 2.

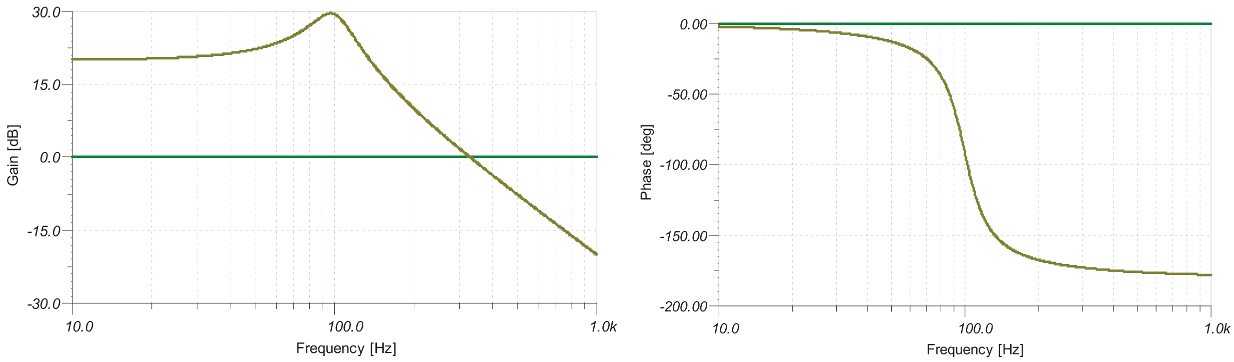


Fig. 2. Results of LPF modeling in the Tina-TI stimulator

According to [12,13] the Q factor can be defined as the distance between the level of 0 dB (in our case, 20 dB) and the maximum frequency response point:

$$Q = 29.61\,dB - 20\,dB = 9.61\,dB = 3.023.$$

According to [9, 14, 15] the frequency of the maximum frequency response point can be defined as:

$$f_m = \frac{1}{2\pi}\sqrt{{\omega_0}^2 - \left(\frac{\omega_0}{2Q}\right)^2} = 98.6\,Hz.$$

The measured value of the frequency of the maximum frequency response point is equal to:

$$f_m\grave{} = 97.02\,Hz.$$

The theoretical values of the parameters and the values of the parameters obtained by simulation match quite well.

Such filter can replace two separate devices connected in series: an amplifier with automatic gain control and a second-order low-pass filter. Automatic gain control can be implemented by changing the coefficient γ. At the same time, the quality factor Q and the frequency of the low-pass filter pole will not change. As an example, such a solution can be applied in modulators of analog radio transmitters to limit the spectrum of the signal and keep it at a constant level.

3 A universal filter of the second - order with independent setting and adjustment of the main parameters

Due to increase the number of OAs, it is possible to create a universal filter with properties similar to the biquad one and the state spase one [6], that is, with the output of low-pass, high-pass and inverted bandpass filters, but with the possibility of independently changing the quality factor and the amplification.

The scheme of such filter is shown in Fig. 3.

The system of Laplace-transformed equations is:

$$\begin{cases} U_1 = -\dfrac{1}{T_1 \cdot p} \cdot U_5 \\ U_2 = -\dfrac{1}{T_2 \cdot p} \cdot U_1 \\ U_3 = U_1 \cdot K_1 - U_2 \cdot K_2 \\ U_4 = -U_3 \cdot K_3 - U_{in} \cdot K_4 \\ U_5 = -U_4 \end{cases}$$

where:

$$K_1 = \frac{R6}{R5 + R6} \cdot \left(1 + \frac{R4}{R3}\right), \quad K_2 = \frac{R4}{R3},$$

$$K_3 = \frac{R9}{R8}, \quad K_4 = \frac{R9}{R7},$$

$$T_1 = R1 \cdot C1, \quad T_2 = R2 \cdot C2$$

p is the Laplace operator.

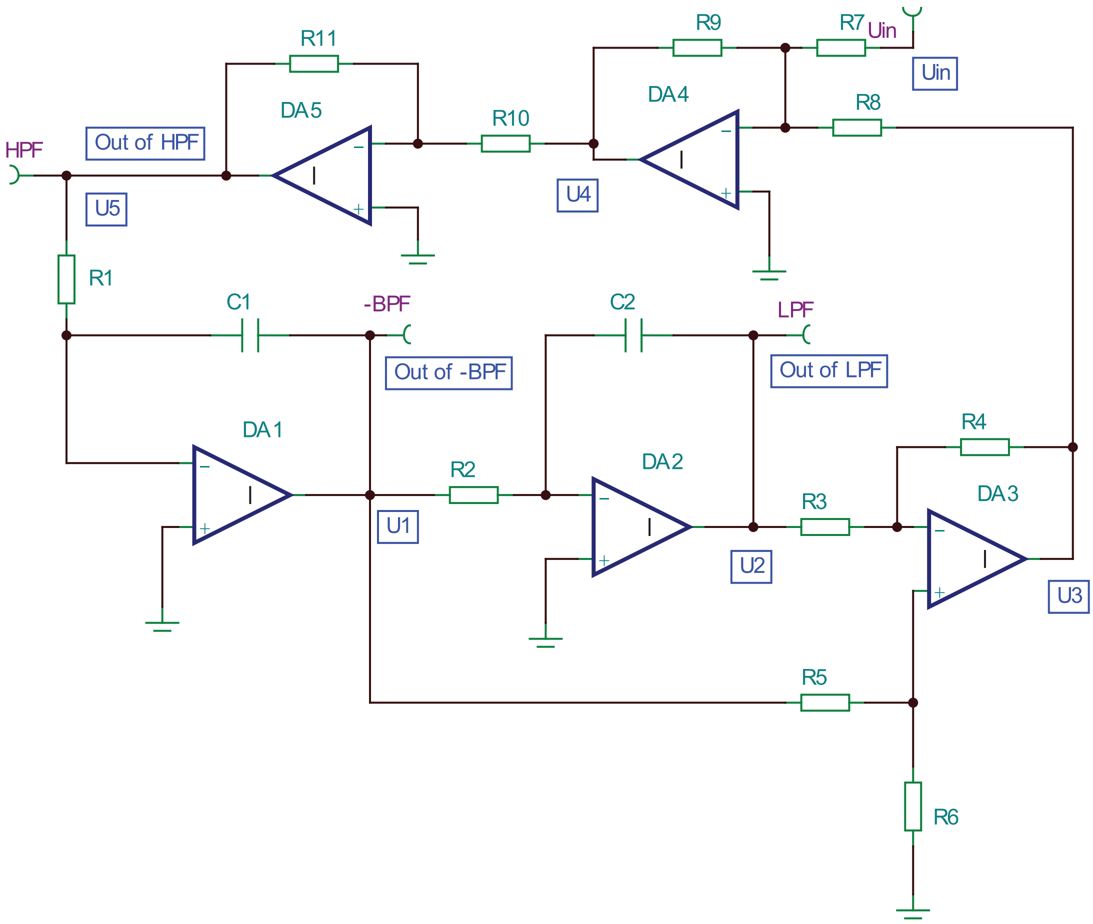


Fig. 3. Scheme of a universal filter

The transfer function for high-pass filter output is:

$$K_{HPF}(p) = \frac{K_{HPF} \cdot p^2}{p^2 + \frac{\omega_0}{Q} \cdot p + {\omega_0}^2},$$

where:

$$\omega_0 = \sqrt{\frac{K_2 \cdot K_3}{T_1 \cdot T_2}}, \quad Q = \frac{1}{K_1} \cdot \sqrt{\frac{T_1 \cdot K_2}{T_2 \cdot K_3}}, \quad K_{HPF} = K_4.$$

The transfer function for low-pass filter output is:

$$K_{LPF}(p) = \frac{K_{LPF} \cdot {\omega_0}^2}{p^2 + \frac{\omega_0}{Q} \cdot p + {\omega_0}^2},$$

where:

$$\omega_0 = \sqrt{\frac{K_2 \cdot K_3}{T_1 \cdot T_2}}, \quad Q = \frac{1}{K_1} \cdot \sqrt{\frac{T_1 \cdot K_2}{T_2 \cdot K_3}}, \quad K_{LPF} = \frac{K_4}{K_2 \cdot K_3}.$$

These formulas show that for both outputs, HPF and LPF, the quality factor and amplification can be adjusted independently, using the K_1 (resistor $R5$ or $R6$) to adjust the quality factor, and the K_4 (resistor $R7$) to adjust the amplification.

If $K_2 = K_3 = 1$ is ensured, then the amplitude-frequency characteristics (frequency response) of the HPF and LPF will be symmetrical with respect to the frequency of the pole ω_0.

Figure 4 presents the results of modeling in Tina-TI of a universal filter with the following parameters: pole frequency $f_0 = 100\,Hz$, quality factor $Q = 3$, amplification $K = 10$.

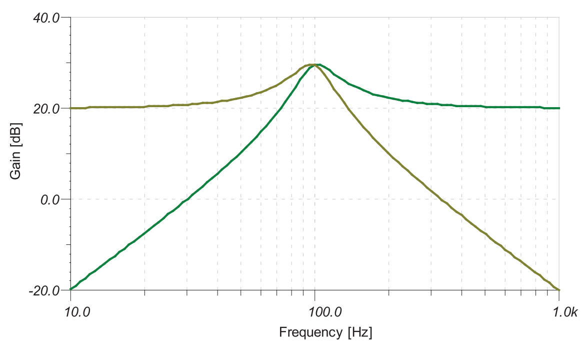


Fig. 4. Frequency response of the filter in Fig. 3 for LPF and HPF outputs if $K_2 = K_3 = 1$ and $f_0 = 100\,Hz$, $Q = 3$, $K = 10$

4 Rejection filter with independent setting and adjustment of main parameters on base of universal filter

When $K_2 = K_3 = 1$, on the basis of this filter, it is possible to synthesize a rejection filter with the possibility of independent adjustment of the amplification and quality factor. To do this, it is necessary to combine the signals from the low-frequency and high-frequency outputs and then invert them. The scheme of this filter is shown in Fig. 5.

The rejection frequency is set using the time constants T_1 and T_2, the required quality factor Q is set using the coefficient K_1 (resistor $R5$ or $R6$), the amplification coefficient K_{RF} – using the coefficient K_4 (resistor $R7$). Graphs of the frequency response of the rejection filter for different values of the quality factor and $f_0 = 100\,Hz, K = 1$ are shown in Fig. 6.

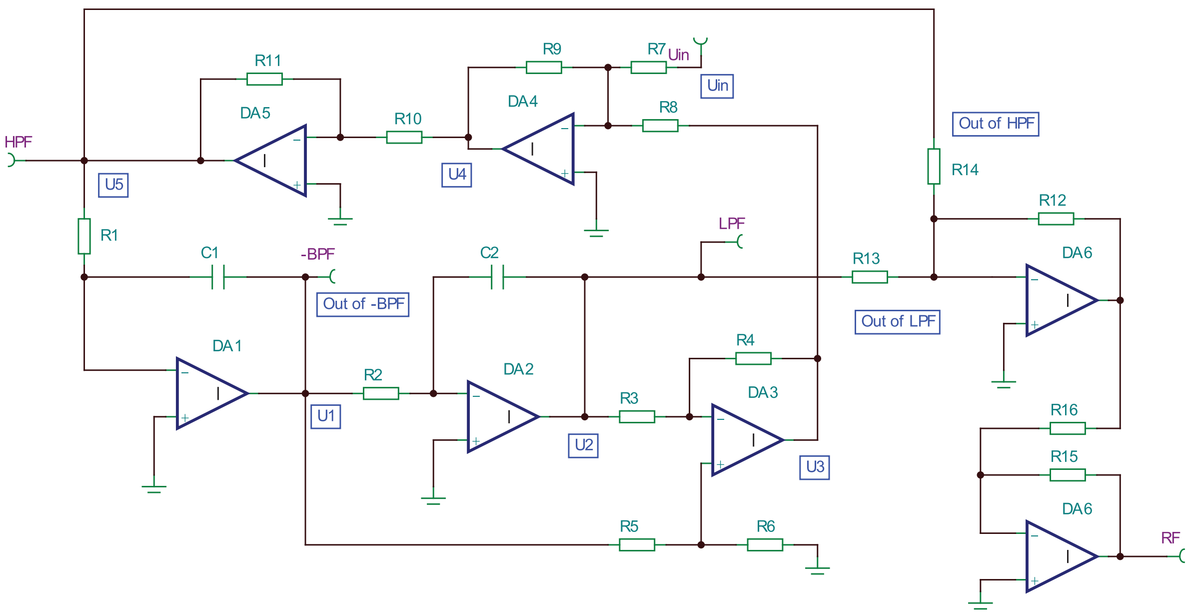
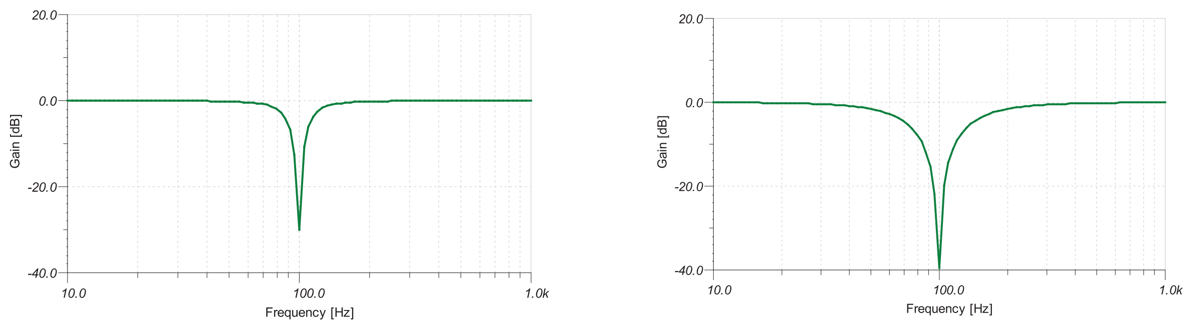


Fig. 5. Rejection filter



(a) (b)

Fig. 6. Frequency response of the rejection filter at different Q values (case (a) $Q = 3$, case (b) $Q = 1$)

Conclusions

The proposed topology of the second-order low-pass filter, which contains three OAs and has the ability to independently adjust the amplification and Q factor. All known topologies that contain three OAs do not have this property.

A universal five-OAs filter that has low-pass, high-pass, and second-order inverted bandpass outputs, which also has the property of independent adjust of Q and amplification for low-pass and high-pass filters outputs. The rejection filter synthesized on the basis of the universal filter also allows independent adjustment of the quality factor and the amplification.

References

[1] Peyton A. J., Walsh V. (1993). *Analog Electronics with Op-amps. A Source Book of Practical Circuits*. Cambrige University Press.

[2] Zieliński, T. P. (2021). *Analog Filters. In: Starting Digital Signal Processing in Telecommunication Engineering. Textbooks in Telecommunication Engineering*. Springer, Cham. doi: 10.1007/978-3-030-49256-4_7.

[3] Wanhammar, L., Saramäki, T. (2020). *Synthesis of Analog Filters. In: Digital Filters Using MATLAB*. Springer, Cham. doi.org/10.1007/978-3-030-24063-9_7.

[4] Wanhammar, L., Saramäki, T. (2020). *Analog Filters with Lumped and Distributed Elements. In: Digital Filters Using MATLAB*. Springer, Cham. doi:10.1007/978-3-030-24063-9_8.

[5] Denisenko D. Y., Prokopenko N. N. and Butyrlagin N. V. (2022). Sallen-Key Dual Channel Low-Pass Filter with Tunable Cutoff Frequency. *2022 IEEE International Multi-Conference on Engineering, Computer and Information Sciences (SIBIRCON)*, pp. 1280-1283, doi: 10.1109/SIBIRCON56155.2022.10016952.

[6] Hank Zumbahlen (ed.) (2008). *Linear Circuit Design Handbook*. Analog Devises, Inc.

[7] Wang S.-F., Chen H.-P., Ku Y., Zhong M.-X. (2021). Analytical Synthesis of High-Pass, Band-Pass and Low-Pass Biquadratic Filters and its Quadrature Oscillator Application Using Current-Feedback Operational Amplifiers. *IEEE Access*, Vol. 9, pp. 13330-13343, DOI: 10.1109/ACCESS.2021.3050751.

[8] Tran, T.T. (2023). *Analog Filter Design. In: High-Speed System and Analog Input/Output Design*. Springer, Cham. doi:10.1007/978-3-031-04954-5_4.

[9] Moschytz G. B., Horn P. (1981). *Active filter design handbook*. John Wiley & Sons.

[10] Pactitis S. A. (2007). *Active filters. Theory and design*. CRC Press, Taylor & Francis Group.

[11] Karki J. (2023). *Active low-pass filter design*. Application note, SLOA049D, Texas Instruments Inc.

[12] Carter B., Mancini R. (2018). *Op Amps for Everyone*, Fifth edition. Elsevier Inc.

[13] Williams A. B. (2014). *Analog filter and circuit design handbook*. Mc Craw Hill education.

[14] Sandoval-Ibarra F., Cuesta-Claros M., Moreno-Espinosa R., Ortiz-Levy E., and Palacios-Betancourt L. (2011). Design of 2nd order low-pass active filters by preserving the physical meaning of design variables. *Revista Mexicana de Física*, Vol. 57, Núm. 1, pp. 1-10.

[15] Scott L. (1966). *Criteria for the design of active filters using resistance and capacitance elements in feedback circuits*. Solid-State Electronics.

Фільтри другого порядку з незалежним встановлюванням і налаштуванням основних параметрів

Антипенко Р. В., Кирпатенко І. М., Мовчанюк А. В., Фесіч В. П.

Запропонована нова топологія фільтра низьких частот другого порядку, що містить три операційні підсилювачі. Як відомо, особливістю фільтрів другого порядку на основі операційних підсилювачів є взаємозалежність основних параметрів фільтра, таких як частота полюса, добротність і підсилення. Найменший взаємозв'язок основних параметрів мають фільтри другого порядку, синтезовані за методом змінних стану, але і вони не дозволяють незалежно налаштовувати коефіцієнт підсилення та добротність, і містять не менше трьох операційних підсилювачів.

Запропонована топологія фільтра низьких частот також містить три операційні підсилювачі і забезпечує можливість незалежної установки частоти полюса, добротності та підсилення, і також можливість незалежного налаштування добротності та підсилення. Отримані співвідношення, які пов'язують частоту полюса, добротність та коефіцієнт підсилення фільтра з номінальними значеннями пасивних елементів фільтра. На основі цих співвідношень показана можливість незалежної зміни добротності та коефіцієнта підсилення фільтра.

На основі такої топології синтезовано універсальний фільтр другого порядку з можливістю незалежного встановлення та налаштування основних параметрів. Запропоновано також режекторний фільтр з незалежною установкою та регулюванням основних параметрів.

Приведені приклади розрахунків фільтра низьких частот другого порядку і результати моделювання, які підтверджують правильність розрахунків. Також наведені результати моделювання універсального і режекторного фільтрів.

Ключові слова: активний фільтр; фільтр другого порядку; частота полюса; добротність