Low-Temperature KHN Active RC Filter Circuit with the Effect of Compensation of Gain Areas of Operational Amplifiers

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Abstract — A new structure of the second-order low-sensitivity active RC filter (ARCF) with an extended frequency range is proposed. The ARCF circuit is implemented on three operational amplifiers (OA) and is recommended as a universal link in the construction of band-pass filters, as well as anti-aliasing low and high pass filters for operation in structures with analog-to-digital converters (ADC). It is shown that, due to the introduction of a new connection, additional difference coefficients appear in the transfer function of the ARCF under consideration, depending on the gain areas (GA) of the OA, which enables to reduce the effect of the frequency properties of the OA on the realizable characteristics at low power consumption. The circuit design of a low-temperature radiation-hardened OA on complementary junction field-effect transistors, designed for operation in severe conditions, is considered.

Keywords — universal active RC filter, anti-aliasing filter, band-pass filter, low-temperature operational amplifier, gain area, KHN filter circuit.

I. INTRODUCTION

Nowadays, analog filtering has been significantly sidelined by digital signal processing (DSP). However, with severe restrictions on energy consumption [1], many tasks of construction of sensor interfaces based only on DSP have not been solved [2,3]. In addition, input analog anti-aliasing filters (spectrum limiters), as a rule, are an integral part of various ADCs [4,5] and affect their errors.

There is a significant number of the second-order filter architectures, providing the selection of a given spectrum of input signals in problems of instrument-making, communication and automation [6-16], including those implementing different principles of work [11,15,2,17,3].

Currently, the theory of analog ARC filters, including for ADC conversion tasks, is developing in the direction of the application of new active elements (AE) [18-20] (differential difference operational amplifiers [21-26], various modifications of current conveyors [27-29,16] and amplifiers with current feedback [30-33]). Active research is being carried out in the field of tunable filters [1,4,3], as well as in the direction of searching for architectures that minimize the influence of the gain area of the AE on the main parameters of the ARCF [34].

However, there are more than 150 types of the AEs today [2,18-20,3], but not all of them are available in the

form of packaged microcircuits or chips. At the same time, the classic OAs, produced by large circulations by leading microelectronic firms, are the most common and cheap AE that are widely used in precision ARCFs [35,36,5,37-42]. Thus, more than 2,000 names of operational amplifiers are represented on the international market of microelectronic products. In this regard, the search for new ARCF architectures on the OA [11,15] is still of interest. In many cases, such ARCFs can be successfully implemented in the basis of new active elements [18, 19, 3].

In space tool engineering, the ARCF design problem for working at low temperatures [43], when low power consumption is necessary, is quite relevant. This requires special architectural solutions [43].

The purpose of this article is to study the properties of the new circuit of the second order universal link, in which the effect of the gain area of the applied OAs, including the low-temperature ones, based on the ARCF amplitude-frequency characteristics (AFC) is reduced. This enables to extend the operating frequency range of the filter or, ceteris paribus, to reduce power consumption due to micro-power OAs.

II. MODIFIED SECOND-ORDER ARC FILTER

To reduce the effect of the GA of operational amplifiers on the amplitude-frequency characteristics of a second-order filter, it is promising to use the circuit shown in Fig. 1 [44], which contains three operational amplifiers (A1, A2, A3) and frequency seed passive elements – resistors R1-R8 and capacitors C1, C2.

Fig. 1. Modified circuit of the universal second-order KHN-filter [44]

Properties of the circuit of Fig. 1, on the basis of which band-pass filters (PF), low (LPF) and high (HPF) pass filters are implemented, are determined by the coefficients of its transfer function $F(p)$, which can be represented by the following formula

$$F(p) = \frac{pb_1}{p^2 + pa_1 + a_0} = M \frac{pd_p \omega_p}{p^2 + pd_p \omega_p + \omega_p^2}, \quad (1)$$

where ω_p – pole frequency, M – filter gain on a pole frequency, d_p – pole attenuation, a_0 , a_1 и b_1 – transfer-function coefficients $F(p)$, p – Laplace variable, $Q_p = 1/d_p$ – Q-factor of the pole.

Q-factor and the transmission coefficient on the frequency of quasi-resonance [6] are relating to the most important parameters of the band-pass filters.

At low frequencies, the frequency properties of operational amplifiers have almost no effect on the amplitude frequency characteristics implemented by the filter circuit, so the basic circuit parameters — the gain factor, frequency and pole attenuation are determined by the parameters of the passive R and C elements. With an increase in the frequency range of the circuit operation, the amplification of the operational amplifiers decreases, which leads to deviation of the main parameters of the circuit from their calculated values, as they become dependent on the frequency characteristics of the OA. Thus, at higher frequencies, the transfer function coefficients (1) become dependent not only on the parameters of the passive elements, but also on the gain areas of the operational amplifiers – GB .

Analysis of various active RC filter circuits shows that the frequency properties of these circuits are determined not only by the parameters of the passive elements and gain areas GB , but also by the circuit topology, i.e. by connections between elements [34]. Thus, only due to the structural optimization of the scheme, i.e. without the inclusion of additional elements, it is possible to achieve the expansion of the frequency range of its operation.

To find the parameters of the transfer function of the proposed scheme of Fig. 1 [44] we use the signal graph method [45]. To do this, we denote the nodes in the circuit of Fig. 2a and compose its signal graph (Fig. 2b).

Fig. 2. The universal ARCF (a) and its signal graph (b)

Let's find the transfer function of the circuit in Fig. 2a from input 1 to output 5, which corresponds to the band-pass filter. Moreover, it can be shown that the transmission of the branches in Fig. 2b is defined by the following formulas:

$$\gamma_{12} = \beta_0 = \frac{R_5 \parallel R_7}{R_6 + R_5 \parallel R_7}; \quad \gamma_{52} = \beta_1 = \frac{R_6 \parallel R_5}{R_7 + R_5 \parallel R_6};$$

$$\gamma_{23}(p) = \frac{1 + k_1 + k_2}{\frac{p}{GB_1}(1 + k_1 + k_2) + 1};$$

$$\gamma_{35}(p) = \frac{-\frac{1}{p\tau_1}}{\frac{p}{GB_2}(1 + \frac{1}{p\tau_1}) + 1};$$

$$\gamma_{36}(p) = \frac{\frac{p}{GB_2}}{\frac{p}{GB_2}(1 + \frac{1}{p\tau_1}) + 1};$$

$$\gamma_{54}(p) = \frac{-\frac{1}{p\tau_2}}{\frac{p}{GB_3}(1 + \frac{1}{p\tau_2}) + 1};$$

$$\gamma_{64}(p) = \frac{1 + p\tau_2}{\frac{p}{GB_3}(p\tau_2 + 1) + p\tau_2};$$

$$\gamma_{43}(p) = \frac{-k_2}{\frac{p}{GB_1}(1 + k_1 + k_2) + 1};$$

where $k_1 = \frac{R_3}{R_8}; \quad k_2 = \frac{R_3}{R_4}; \quad \tau_1 = R_1 C_1;$
 $\tau_2 = R_2 C_2.$

As a result, the transmission from the input of the band-pass filter to its output OutBF, can be found using Mason's gain formula

$$F_{15}(s) = \frac{\gamma_{12}\gamma_{23}\gamma_{35}}{1 - \gamma_{23}\gamma_{35}\gamma_{52} - \gamma_{35}\gamma_{54}\gamma_{43} - \gamma_{43}\gamma_{36}\gamma_{64}}.$$

Substituting the transmissions of branches in the last formula and comparing the resulting expression with formula (1), we find the idealized parameters of the considered circuit in Fig. 2a:

- transmission coefficient on the pole frequency

$$M = \frac{R_7}{R_6}, \quad (2)$$

- pole frequency

$$\omega_p = \sqrt{\frac{k_2}{\tau_1 \tau_2}}, \quad (3)$$

- pole attenuation

$$d_p = (1 + k_1 + k_2) \frac{\beta_1}{\sqrt{k_2}} \sqrt{\frac{\tau_2}{\tau_1}}. \quad (4)$$

The gain factor of the nonideal OA depends on the frequency. In many cases, the corrected OA can be represented by the first-order transfer function.

$$F_{OA}(p) = \mu \frac{\omega_{oa}}{p + \omega_{oa}} = \frac{GB}{p + \omega_{oa}}, \quad (5)$$

where μ – gain factor of the OA at the direct current (on zero frequency), ω_{oa} – boundary frequency of the OA (the frequency on which μ decreases to the level of 0.707μ), GB – gain area of the OA.

Taking into account the limited band-pass of the OA (5) in Fig. 2 the scheme analysis showed that the coefficients of the denominator of its transfer function (1) are defined by the following expressions:

$$a_1 = \frac{\frac{\beta_1(1+k_1+k_2)}{\tau_1} + \frac{\beta_1(1+k_1+k_2)}{GB_3\tau_1\tau_2}}{1 + \frac{1}{GB_2\tau_1} + \frac{1}{GB_2\tau_2} + \frac{k_2}{GB_1\tau_1} + \frac{\beta_1(1+k_1+k_2)}{GB_3\tau_1}} - \frac{\omega_p^2 \left(\frac{1}{GB_3} + \frac{1}{GB_2} + \frac{1+k_1+k_2}{GB_1} \right) + \frac{k_2}{GB_2\tau_1\tau_2}}{1 + \frac{1}{GB_2\tau_1} + \frac{1}{GB_2\tau_2} + \frac{k_2}{GB_1\tau_1} + \frac{\beta_1(1+k_1+k_2)}{GB_3\tau_1}}, \quad (6)$$

$$a_0 = \frac{\frac{k_2}{\tau_1\tau_2}}{1 + \frac{1}{GB_2\tau_1} + \frac{1}{GB_2\tau_2} + \frac{k_2}{GB_1\tau_1} + \frac{\beta_1(1+k_1+k_2)}{GB_3\tau_1}}. \quad (7)$$

where GB_1 , GB_2 , GB_3 – gain areas of OAs A1, A2 and A3 correspondingly.

Let's carry out a similar analysis of the widely used circuit of Fig. 3a, which is known as a universal KHN filter [10,25].

Fig. 3. Circuit of the classic KHN filter (a) and its graph (b)

For the circuit of Fig. 3a, the transfer function coefficients, similar to formulas (6) - (7), are determined by the following equations:

$$a_1 = \frac{\frac{\beta_1(1+k_1+k_2)}{\tau_1} + \frac{\beta_1(1+k_1+k_2)}{GB_3\tau_1\tau_2}}{1 + \frac{1}{GB_2\tau_1} + \frac{1}{GB_2\tau_2} + \frac{\beta_1(1+k_1+k_2)}{GB_3\tau_1}} - \frac{\omega_p^2 \left(\frac{1}{GB_3} + \frac{1}{GB_2} + \frac{1+k_1+k_2}{GB_1} \right) + \frac{k_2}{GB_2\tau_1\tau_2}}{1 + \frac{1}{GB_2\tau_1} + \frac{1}{GB_2\tau_2} + \frac{\beta_1(1+k_1+k_2)}{GB_3\tau_1}}, \quad (8)$$

$$a_0 = \frac{\frac{k_2}{\tau_1\tau_2}}{1 + \frac{1}{GB_2\tau_1} + \frac{1}{GB_2\tau_2} + \frac{\beta_1(1+k_1+k_2)}{GB_3\tau_1}}. \quad (9)$$

It should also be noted that from formulas (6) - (9), when $GB \rightarrow \infty$, the idealized parameters of filter circuits

(2) - (4) can be found. The same formulas are also valid for filter circuits operating on low frequencies, where the effect of the gain areas of the OA is negligible.

III. THE CIRCUIT DESIGN OF THE OA FOR OPERATION AT LOW TEMPERATURES, INCLUDING THE CRYOGENIC ONES

The stability of the implemented parameters of active RC-filters depends not only on the temperature coefficients of resistances and capacitors, but also on the properties of the active elements, which must keep their parameters in a wide temperature range. In this regard, when designing ARC filter circuits, it is advisable to use the OA, the circuit design of which was developed taking into account their work up to cryogenic temperatures [43].

Low noise cryogenic operational amplifiers can be implemented on complementary junction field-effect transistors (JFET). The proposed scheme of such OA (Fig. 4) contains non-traditional input stage and a buffer amplifier based on the JFET properties of the active elements of OAO "Integral" (Minsk).

Fig. 4. The simplified electric circuit of cryogenic OA of JFET_OAmp3

The results of computer simulation of the OA circuit of Fig. 4 at the temperature $T = -197^\circ\text{C}$ are presented in Fig. 5.

Fig. 5. The amplitude-frequency and phase-frequency characteristics of the DDOA OAmp3 at $T = -197^\circ\text{C}$

IV. THE RESULTS OF COMPUTER SIMULATION OF THE BAND-PASS FILTER

Fig. 6 shows the simulation results of the new filter circuit of Fig. 1 for PF output and the well-known universal KHN filter of Fig. 3a on different frequencies of quasiresonance in the range from 10 to 100 kHz.

From the analysis of graphs in Fig. 6 it follows that with the same OAs, including Fig. 4, in the compared circuits, the frequency range of the new scheme is expanded by approximately one and a half times. In this case, the relative winning on the frequency range will be the higher, the smaller the GA of the applied OA.

Similar results can be obtained for the low and high pass filter outputs. However, deriving the basic equations for these ARCF versions we should take into account the effect of $GB1$, $GB2$, $GB3$ on the coefficient b_1 in formula (1).

Fig. 6. The amplitude frequency characteristic of the new circuit (1) and the KHN-filter circuit (2)

V. CONCLUSION

The proposed circuit of the universal filter of the second order reduces the effect of the gain area GA of the operational amplifiers on the amplitude frequency characteristics. Depending on Q factor implemented and the frequency properties of the OA, the frequency range of the considered band-pass filter is approximately 1.5 times larger than in the widely used classical KHN filter. Moreover, this effect is achieved without any additional elements – due to the introduction of a single new connection between the elements of the well-known KHN filter (connection of the non-inverting input of OA A2 with the non-inverting input of OA A3).

In the studied filter circuit, micropower OAs can be used, which enables us to recommend it for the use in low-temperature analog-digital interfaces of automation and communication systems. The application of the proposed circuit design solution is also promising when implementing the ARC filters on new classes of active elements, including the differential difference operational amplifiers and the cryogenic ones.

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