Low pass anti-alias filter for ADC with differential input on base Op-Amp with differential output with a minimum number of capacitors

D Yu Denisenko1,2, N N Prokopenko1,3 and N V Butyrlagin1

1Don State Technical University, Gagarin Sq. 1, Rostov-on-Don, 344000, Russia
2Southern Federal University, Bolshaya Sadovaya St. 33, Rostov-on-Don, 344000, Russia
3Institute for Design Problems in Microelectronics of Russian Academy of Sciences, IPPM RAS, Zelenograd, 124681, Russia

Email: d.u.denisenko@gmail.com

Abstract. The new circuit of third order low-pass filter (LPF) on operational amplifier (Op-Amp) with differential output designed to limit the spectrum of signals at the input of an analog-to-digital converter (ADC) is presented. The developed circuit contains one capacitor less than in classical LPF. The basic equations of the new circuit are presented and the results of computer simulation obtained in Micro-Cap CAD, which based on models of THS4130 Op-Amp by Texas Instruments, are shown. The results of computer simulation confirm the efficiency of this LPF scheme and show a close to ideal correspondence between the theoretical and real amplitude-frequency response.

1. Introduction

Active analog and digital RC low-pass filters (LPF) are widely used in modern electronics, for example, as spectrum limiters [1-3], included at the input of analog-to-digital converters for various purposes [3] and have a significant impact on the quality indicators of many analog-to-digital communication systems and automatic control.

Active LPF can be implemented on differential (Op-Amp) [4-7] and differential difference operational amplifiers (DDA) [7-17]. Active capacitive LPF have smaller dimensions and weight than passive inductive LPF, which is one of the indisputable advantages of these devices [18,19]. The order of the LPF depends on the number of reactive elements (capacitor) in the filter circuit. Increasing the order of the filter leads to a complication of the filter circuit, its rise in price, and most importantly the filter becomes very sensitive to the spread of the nominal values of its elements and requires precise precision tuning [4-17].

The purpose and novelty of the article is to create a third-order LPF containing a reduced (in the third order of the transfer function) number of capacitors, providing an increase in the guaranteed attenuation of the amplitude-frequency response than in classical LPF.
2. The low-pass filter based on operational amplifier with differential output

The circuit of the classical LPF is shown in figure 1 [20]. A significant drawback of this scheme is that in the third order of the transfer function, it has five frequency-limiting capacitors. Also, high attenuation of spurious signals outside the frequency band of the useful signal is not achieved here. As a result, this negatively affects the metrological characteristics of measurement systems and analog input devices in computers, in which the LPF determines the dynamic error of the analog-to-digital interface [21].

![Classical circuit of third order low-pass filter](image)

**Figure 1.** Classical circuit of third order low-pass filter [20].

The basic equations of the scheme in figure 1 are presented in [20]. A new LPF circuit, also implemented on the basis of Op-Amp with differential output, is shown in figure 2. Similarly, in the circuit (figure 1) the input signal is fed to the differential input In.1, In.2, and the output signal is removed from the differential output of the Out.1, Out.2. The peculiarity of this scheme consists in a smaller number of frequency-setting elements (capacitors) in the implementation of the third-order LPF [22].

The transfer function of the LPF circuit of the third order, including the low-pass filter (figure 2), is generally described by the expression

\[
F(p) = \frac{V_{\text{out}}(p)}{V_{\text{in}}(p)} = M \frac{a_0}{p^3 + a_2 p^2 + a_1 p + a_0},
\]

where \( M \) is the transmission coefficient of the filter at zero frequency, \( a_2 \ldots a_0 \) are the coefficients of the transfer function depending on the topology of the circuit and the parameters of its elements.

We introduce notation: \( R_1, R_2, R_3, R_4, R_5, R_6, R_7, R_8 \) is resistance of resistors \( R_1, R_2, R_3, R_4, R_5, R_6, R_7, R_8 \); then \( C_1, C_2, C_3, C_4 \) is capacitance of capacitor \( C_1, C_2, C_3, C_4 \) respectively.
Under a number of conditions $R_1 = R_2$, $R_3 = R_4$, $R_5 = R_6$, $R_7 = R_8$, $C_2 = C_3$, which in the circuit (figure 1) it is necessary to provide for the symmetrical operation of the filter channels, the transfer function coefficients (1) are found using the following expressions:

$$M = \frac{R_5}{R_1}, \quad (2)$$

$$a_2 = \frac{1}{2R_5C_1} + \frac{1}{2R_1C_1} + \frac{1}{2R_3C_1} + \frac{1}{2R_7C_4}, \quad (3)$$

$$a_1 = \frac{1}{2R_5R_7C_4C_1} + \frac{1}{2R_1R_7C_4C_1} + \frac{1}{2R_7R_3C_4C_1} + \frac{1}{2R_5R_3C_1C_2}, \quad (4)$$

$$a_0 = \frac{1}{2R_3R_1R_7C_1C_2C_4}. \quad (5)$$

3. Result of computer simulation

Computer simulation of the LPF circuit (figure 2) was run in Micro-Cap environment [23-26] (figure 3) on based on models of THS4130 Op-Amp [27] by Texas Instruments. In June of 2018, Micro-Cap 12 was released [25] and is a mixed analog-digital circuit analysis program for personal computers. Micro-Cap 12 is the twelfth generation of a program that began in 1982 with the release of Micro-Cap. Since then it has acquired many refinements, always adhering to its primary goal of providing an easy to use, sketch and simulate environment [25].
Figure 3. The third-order low-pass filter circuit (figure 2) in the MicroCap environment [24].

In figure 4 we can see the results of computer simulation the amplitude-frequency response of the developed LPF (figure 3) (curve 1 – for LPF with real operational amplifiers THS4130 [27], curve 2 – theoretical characteristic of LPF, calculated by the equation (1)).

Figure 4. Results of computer simulation is a amplitude-frequency response of LPF (figure 3).

Analysis of the characteristics in figure 4 shows that the low-pass filter circuit (figure 2) provides (curve 1) close to ideal (theoretical) amplitude-frequency response (curve 2) with four frequency-limiting capacitors [22].
4. Conclusion

It is shown that the proposed third-order low-pass filter based on the op-amp with differential output has one less frequency-setting capacitor than in classical low-pass filters. In its implementation, high attenuation of spurious signals outside the frequency band of the useful signal is provided.

Reducing the number of capacitors makes it easier to configure the LPF, as the most critical element of modern filters, which at the present stage of electronics development is characterized by a large spread of parameters and their instability in the temperature range.

The developed low-pass filter is recommended as an anti-aliasing filter to limit the spectrum of signals at the input of an ADC with a differential input.

Acknowledgments

The research is carried out at the expense of the Grant of the Russian Science Foundation (project № 18-79-10109).

References

[1] Zolotarev A V 2012 Drift-free Spectrum Limiters with Extended Frequency Range Journal of Izvestia SPU. Technical science, Section II. Complex functional blocks of mixed systems on a chip 2 71–6

[2] Ma S and Chen Y 2011 Implementation and Design of Carrier Recovery Loop for High Order QAM Signals Proc. 7th IEEE Int. Conf. on Wireless Communications, Networking and Mobile Computing (Wuhan) pp 1–4 DOI: 10.1109/wicom.2011.6040120

[3] Wolf M H and Vogel D 1989 DSP Method to Receive Spread Spectrum Signals Proc. Int. Conf. on Acoustics, Speech, and Signal Processing vol 2 (Glasgow, United Kingdom) pp 1263–6 DOI: 10.1109/ICASSP.1989.266665

[4] Chapagai K, Bahubalindruni P and Nishtha 2018 2nd Order Sallen Key Switched Capacitor LPF with N-type Transistors Proc. 31st IEEE Int. Conf. on VLSI Design and 2018 17th IEEE International Conference on Embedded Systems (VLSID) (Pune, India) pp 319–24 DOI: 10.1109/VLSID.2018.83

[5] Ye L, Shi C, Liao H, Huang R and Wang Y 2013 Highly Power-Efficient Active-RC Filters With Wide Bandwidth-Range Using Low-Gain Push-Pull Opamps IEEE Transactions on Circuits and Systems I: Regular Papers 60(1) 95–107 DOI: 10.1109/TCSI.2012.2215700

[6] D’Amico S, De Blasi M, De Matteis M and Baschirrotto A 2012 A 255 MHz Programmable Gain Amplifier and Low-Pass Filter for Ultra Low Power Impulse-Radio UWB Receivers IEEE Transactions on Circuits and Systems I: Regular Papers 59 (2) 337–45 DOI: 10.1109/TCSI.2011.2163886

[7] Wu C, Hsieh H, Ku P and Lu L 2010 A Differential Sallen-Key Low-Pass Filter in Amorphous-Silicon Technology IEEE Journal of Display Technology 6(6) 207–14 DOI: 10.1109/JDT.2010.2044631

[8] Wang L H, Chen T Y, Lee S Y, Yang T H, Huang S Y, Wu J H, Lin K H and Fang Q 2012 A Wireless ECG Acquisition SoC for Body Sensor Network Proc. IEEE Biomedical Circuits and Systems Conf., BioCAS (Hsinchu, Taiwan) pp 156–9 DOI: 10.1109/BioCAS.2012.6418396

[9] Prokopenko N N, Butyrlagin N V, Krutchinsky S G, Zhebrun E A and Titov A E 2015 The Advanced Circuitry of the Precision Super Capacitances Based on the Classical and Differential Difference Operational Amplifiers Proc. IEEE 18th Int. Symp. on Design and Diagnostics of Electronic Circuits & Systems, DDECS (Belgrade, Serbia) 111–4 DOI: 10.1109/DDECS.2015.46

[10] Denisenko D Y, Prokopenko N N and Butyrlagin N V 2019 All-Pass Second-Order Active RC-Filter with Pole Q-Factor’s Independent Adjustment on Differential Difference Amplifiers
[11] Stornelli V, Pantoli L, Leuzzi G and Ferri G 2013 Fully Differential DDA-Based Fifth and Seventh Order Bessel Low Pass Filters and Buffers for DCR Radio Systems Analog Integrated Circuits and Signal 75 (2) 305–10 DOI: 10.1007/s10470-013-0051-9

[12] Kumnegn M and Klangthanh K 2017 0.5-V Fourth-Order Low-Pass Filter Proc. IEEE 2nd Int. Conf. on Automation, Cognitive Science, Optics, Micro Electro-Mechanical System, and Information Technology, ICACOMIT (Jakarta, Indonesia) pp 119–22 DOI: 10.1109/ICACOMIT.2017.8253398

[13] Hu Q, Yang L and Huang F 2016 A 100–170MHz Fully-Differential Sallen-Key 6th-order Low-Pass Filter for Wideband Wireless Communication Proc. Int. Conf. on Integrated Circuits and Microsystems, ICICIM (Chengdu, China) pp 324–8 DOI: 10.1109/ICAM.2016.7813617

[14] Lai L S, Hsieh H H, Weng P S and Lu L H 2009 An Experimental Ultra-Low-Voltage Demodulator in 0.18-um CMOS IEEE Transactions on Microwave Theory and Techniques 57 (10) 2307–17 DOI: 10.1109/TMTT.2009.2029023

[15] Khateb F, Kumnegn M, Kulej T and Kledrowetz V 2018 Low-voltage fully differential difference transconductance amplifier IET Circuits, Devices & Systems 12 (1) 73–81 DOI: 10.1049/iet-cds.2017.0057

[16] Shi C, Wu Y, Elwan H O and Ismail M 2000 A low-power high-linearity CMOS baseband filter for wideband CDMA applications Proc. IEEE Int. Symp. on Circuits and Systems, ISCAS vol 2 (Geneva, Switzerland) pp 152–5 DOI: 10.1109/ISCAS.2000.856281

[17] Singh B, Kumar Singh A and Senani R 2013 A new universal biquad filter using differential difference amplifiers and its practical realization Analog Integrated Circuits and Signal Proc. 75 (2) 293–7 DOI: 10.1007/s10470-013-0048-4

[18] Low Pass Filter- Explained http://www.learningaboutelectronics.com/Articles/Low-pass-filter.php

[19] Yuce E, Minaei S and Ciccekoglu O 2006 Limitations of the Simulated Inductors Based on a Single Current Conveyor IEEE Transactions on Circuits and Systems I: Regular Papers 53 (12) 2860-67 DOI: 10.1109/TCSI.2006.883872

[20] Denisenko D Yu, Zhebrun E A, Bulgakova A V and Prokopenko N N 2019 Active third-order RC low-pass filter with differential input based on an operational amplifier with a paraphase output RU Patent 2695981

[21] Samoylov L K, Denisenko D Y and Prokopenko N N 2018 The Function Approximation of the Signal Delay Time in the Anti-Alias Filter of the A/D Interface of the Instrumentation and Control System Proc. IEEE Int. Conf. on Electrical Engineering and Photonics, EExPolytech (St. Petersburg, Russia) pp 18–21

[22] Denisenko D Yu, Prokopenko N N and Ignashin A A 2019 A third order low pass filter with a minimum number of capacitors by an order of magnitude RU Patent appl. 2019137446

[23] Micro-Cap 10 Electronic Circuit Analysis Program User's Guide https://www.spectrumsoft.com/download/ug10.pdf

[24] Micro-Cap 11 Electronic Circuit Analysis Program Reference Manual https://www.iee.et.tudresden.de/~jmueller/simulation/soft/microcap/MC11.RefManual.pdf

[25] Micro-Cap 12 Electronic Circuit Analysis Program User's Guide http://www.spectrumsoft.com/download/ug12.pdf

[26] Artuhov V and Brytov O 2019 FIR Filter Design by Micro-Cap Tools Proc. IEEE 39th Int. Conf. on Electronics and Nanotechnology, ELNANO (Kyiv, Ukraine) pp 626–9 DOI: 10.1109/ELNANO.2019.8783575

[27] THS413x High-Speed, Low-Noise, Fully-Differential I/O Amplifiers http://www.ti.com/lit/ds/symlink/ths4131.pdf