Third-Order Low-Pass Filters for Limiting the Signal Spectrum at the Differential Input of the Analog/Digital Converters

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Abstract. Two new architectures of the third-order low-pass filters (LPF) based on differential (Op-Amp) and differential difference amplifiers (DDA) with a paraphase output are compared. This architectures designed for practical use as anti-aliasing filters in analog-to-digital converters of sensor signals of various physical quantities. The basic equations of the developed LPF modifications that make possible to perform their parametric synthesis are given. The computer simulation results are presented, which show that the LPFs under consideration provide the guaranteed frequency response (FR) attenuation outside the bandwidth being implemented on Op-Amps by Analog Device (AD8132) and Texas Instruments (THS4131).

1. Introduction

Active low-pass RC-filters (ARCFs) are widely used as spectrum limiters [1-4] at the input of the analog/digital converters (ADCs) of modern automatic control systems and have a significant impact on their quality indicators. Wherein, for a promising class of the ADCs with a differential input, with increased noise immunity, the anti-aliasing RC-filters with a differential output are required, permitting an independent adjustment of their main parameters [5].

The third-order LPFs providing the extraction of a given spectrum of the input signals with different quality indicators for specific tasks of tool engineering and automation [6-9], are implemented on various topologies, as well as with diverse active elements (differential [10, 11] and differential difference amplifiers (DDA) [12], amplifiers with current feedback [13, 14], current conveyors [15, 16], OTA-amplifiers [17, 18]). However, it should be noted that the search for promising LPF structures is still an urgent task of the modern theory of the ARC-filters, oriented to work with modern analog-to-digital converters automation and control devices.

The purpose and novelty of the article are to develop and study the properties of two new LPF modifications [19, 20] based on the Op-Amps (OAs) and the DDAs, which can be used to limit the...
signal spectrum at the differential input of the ADC and allow made an independent adjustment of the main parameters.

2. Basic equations of the third-order LPF

In general terms the transfer function of the classical third-order LPFs is described by the expression [19]

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

where \(M\) is a filter gain on zero frequency, \(a_2...a_0\) are transfer function gains, depending on the topology of a particular LPF circuit and the parameters of its elements.

The LPF circuits considered below are described by equation (1).

3. LPF with a single-ended input

Figure 1 shows the first modification of the LPF [19]. Its task is to increase the guaranteed frequency response (FR) attenuation outside the bandwidth up to the level of theoretical values of this parameter when using AD8132 Op-Amp.

![Figure 1. The LPF with a nondifferential input.](image)

The transfer function gains (1) for the LPF of figure 1 are defined by the expressions

\[
M = \frac{R_1}{R_4},
\]

\[
a_2 = \frac{1}{R_2 C_1} + \frac{1}{R_3 C_3} + \frac{1}{R_1 C_1} + \frac{1}{R_2 C_3} + \frac{1}{R_1 C_3} + \frac{1}{R_2 C_2},
\]

\[
a_1 = \frac{1}{R_2 R_4 C_1 C_2} + \frac{1}{R_2 R_4 C_1 C_3} + \frac{1}{R_2 R_4 C_2 C_3} + \frac{1}{R_1 R_4 C_1 C_3} + \frac{1}{R_1 R_4 C_2 C_3} + \frac{1}{R_1 R_4 C_3 C_3}
\]

\[
a_0 = \frac{1}{R_2 R_4 R_1 C_1 C_2 C_3},
\]

where \(R_1, R_2, R_3, R_4\) are resistances of resistors \(R_1, R_2, R_3, R_4\), respectively, \(C_1, C_2, C_3\) are capacitances of capacitors \(C_1, C_2, C_3\).

Figure 2 shows the FR of the LPF in figure 1, obtained as a result of simulation of a circuit with real AD8132 Op-Amp [24] (line "1") and as a result of theoretical calculations by formula (1) is line "2". The discrepancy in the high-frequency region of the FR of figure 2 obtained by modeling the LPF (line "1") from the R obtained by calculation (line "2") is associated with the influence of the frequency properties of AD8132 Op-Amp [24], which was not taken into account when determining the coefficients (2), include in (1). In fact, the LPF of Figure 1 with specific operational amplifier
AD8132 [21] gives a higher attenuation of input signal (points A, B, C on figure 2) than an ideal theoretical LPF described by (1).

![Graph showing the Frequency Response of the LPF](image)

**Figure 2.** The FR of the LPF circuit (Figure1).

Figure 3 shows a modified LPF circuit for the case where a DDA is used as Op-Amp [19]. Its feature is the presence of a circuit for establishing a defined static mode (DSM) [22], which solves the problem of digital control of zero level in the LPF outputs to obtain the extreme range of the output voltage changes. The DSM circuit can be performed on the switched resistors or digital potentiometers [22].

![Diagram of the LPF with DSM](image)

**Figure 3.** The LPF on the DDOA with a static-mode control circuit in Out.1 and Out. 2.

4. **The LPF with differential input and output**

Figure 4 shows the LPF circuit [23], designed to operate with a differential signal source. It has a differential output, which enables us to connect the circuit of figure 4 in the input of the ADC with a differential input.
We analyzing the operation of the circuit of figure 4 and introduce the following notation: $R_1$, $R_2$, $R_3$, $R_4$, $R_5$, $R_6$, $R_7$, $R_8$ are resistances of resistors $R_1$, $R_2$, $R_3$, $R_4$, $R_5$, $R_6$, $R_7$, $R_8$, respectively, $C_1$, $C_2$, $C_3$, $C_4$, $C_5$ – capacitances of capacitors $C_1$, $C_2$, $C_3$, $C_4$, $C_5$.

Subject to certain conditions

$$R_1 = R_2, \quad R_4 = R_3, \quad R_5 = R_6, \quad R_7 = R_8, \quad C_2 = C_3, \quad C_3 = C_4,$$

which should be provided for the balanced operation of the LPF channels, the transfer function gains (1) are found by the following formulas:

$$M = \frac{R_3}{R_1},$$

$$a_2 = \frac{1}{2R_2C_1} + \frac{1}{R_2C_2} + \frac{1}{2R_2C_1} + \frac{1}{R_2C_3} + \frac{1}{2R_2C_1} + \frac{1}{R_2C_3},$$

$$a_1 = \frac{1}{2R_2C_1C_2} + \frac{1}{2R_2C_1C_2} + \frac{1}{2R_2C_1C_2} + \frac{1}{2R_2C_1C_2} + \frac{1}{2R_2C_1C_2},$$

$$a_0 = \frac{1}{2R_2C_1C_2C_3}.$$

Figure 5 presents a comparison of three FR of the LPF circuit of figure 4 obtained by computer simulation on Op-Amps THS4131 [23] (line "1"), AD8132 [21] (line "2") and theoretical calculations (line "3") performed according to Equation (1).
A slight deviation of the FR in the high frequency region (greater than 50÷80 MHz) obtained as a result of simulation of the circuit in figure 4 with real Op-Amps (lines "1", "2") from the FR obtained by calculation (line"3") by (3), is associated with the influence of the frequency properties of the Op-Amp, which was not taken into account when searching the functions (1), (3).

The analysis of the graphic charts of figure 5 obtained for different types of applied Op-Amps (THS4131 [23] and AD8132 [21]), shows a high coincidence of theoretical calculations and computer simulations in the frequency range up to 50÷80 MHz. Moreover, on these frequencies, the FR attenuation exceeds 120 dB, which is sufficient for many applications in modern ADC.

In the proposed LPF of figure 4, it is possible to independently adjust and optimize the main parameters [5] by changing the resistances of resistors $R_1$, $R_7$, $R_3$. This is explained by the fact that here the gain factor $M$ on zero frequency is determined by the ratio

$$M = \frac{R_7}{R_1}$$

In this case, resistor $R_3$ can be used to set the specified values of other parameters of the FR. This enables us to further optimize other parameters of the circuit and get a new quality in the LPF - greater freedom in choosing the parameters of passive elements [20].

5. Conclusion

Two third-order LPF architectures have been developed on the Op-Amp and DDA with a paraphase output, providing high attenuation of the FR outside the bandwidth.

The computer simulation results obtained for various types of the applied Op-Amps show their high coincidence with theoretical calculations.

The differential outputs of the proposed LPFs are low-resistance Op-Amp outputs. This ensures good matching of the LPFs when the following filtering and signal processing stages are connected to it, for example, the ADC inputs in modern analog-to-digital automatic control systems.

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