

INCREASING Q-FACTOR OF THE DIGITAL SENSOR SIGNALS PROCESSING PATH IN AUTONOMOUS MOBILE ROBOTIC PLATFORMS WITH LIMITED COMPUTING RESOURCES

T. V. Sytnikov¹¹Odessa National Polytechnic University

Abstract. The paper is considered the problem of constructing autonomous mobile robotic platform with the possibility of rearranging their characteristics depending on the operating conditions. A new approach is proposed for calculating the parameters of a new connection with a series connection of low-order components of the same type. The resulting ratio allows you to accurately calculate the frequencies of the n -th connection of the same type components. Such a connection allows increasing the quality factor characteristic of the amplitude frequency characteristic and reducing the bandwidth by 3 times with eight connected filters of the same type. Bandpass filters and notch Butterworth filters are considered. Behavior of the AFC for serial connection is described.

Key words: amplitude frequency characteristic, phase frequency characteristic, Industry 4.0-6.0, digital filter, bandpass filter, notch filter, quality factor characteristics, frequency dependent component, notch filter based on bandpass filter, serial connection.

Introduction

The construction of autonomous mobile robotic platforms (AMRP) with limited computing resources for various purposes is not a trivial task, since such platforms have the need to autonomously solve a large number of problems in analyzing the internal state of the platform, its relationship with the environment, orientation in space, planning and solving target problems. Therefore, AMRP cannot function without computing components and a large number of sensors and actuators.

With limited computing resources and a large number of ongoing tasks, autonomous platforms very well fit into the concepts of Industry 4.0, 5.0 and 6.0. In accordance with them, platforms and their components must meet new requirements for mobility, flexibility, adaptability, adaptability to operating conditions. In addition, they must create integrated and connected systems capable of exchanging information [1-5].

In general, the use of such computing components in autonomous mobile robotic systems can support the requirements of all three industrial stages, as they provide real-time data processing, adaptability to changing conditions, and increased efficiency in sensing the environment. The final choice of the concept will depend on the specific needs and development strategy of a particular system.

It should be noted that AMRP is an important

element in building intelligent control systems for multiple platforms that can adapt to changing operating conditions in real time. That's why a set of multi-functional sensors, hardware and software components of computer technology and actuators that must operate in real time are added to the system.

The AMRP must include components that can rearrange their own characteristics using software or hardware depending on operating conditions. In the sensor signal processing path it is necessary to include components that adapt depending on the presence of interference and noise to increase the reliability and efficiency of the system as a whole.

Digital devices which are using to process sensor signals include various frequency-dependent components. [6] In AMRP with limited computing resources, such components are produced on the basis of low-order components. This is due to the low cost of calculating the transfer function coefficients and the number of coefficients, ease of debugging or restructuring, moderate power consumption and processing time. When working in real time, there is a limitation on the calculation, restructuring and transient process of the new configuration of the signal processing unit. First and second order components are often used as low order components.

When using such components, typical tasks in difficult operating conditions are changing the bandwidth of the processing unit and increasing the steepness of the amplitude frequency characteristic (AFC).

A typical sensor signal processing unit is a series connection of frequency-dependent components. Then, when the transfer functions of components of the same type are connected in series, their transfer functions are multiplied. Since the transfer functions consist of amplitude-frequency (AFC) and phase-frequency (PFC) characteristics, and the components are of the same type, then when similar components are cascaded together, their characteristics are multiplied by proceeding to exponentiation. In this case, their characteristics of the AFC and PFC are respectively transformed as follows: the AFC is raised to a degree, and the PFC is multiplied by the exponent. Then, with such a connection, the main changes occur in the AFC [7-9].

The purpose of the research is to analyze the series connection of the same type of frequency-dependent components to increase the Q-factor of the AFC of strip elements and to search for new computational formulas. Let's consider this using the example of bandpass and notch digital filters, since they are widely used in signal processing units of AMRP sensors.

1. Quality factor characteristic of digital bandpass filters

It is known that the Q-factor (quality factor characteristic QFC) of bandpass filters is determined by their AFC [6]. To do this, determine the bandwidth B as the difference in cutoff frequencies at a level of 0.707 (approximately -3 dB) from the height of the AFC maximum, because half of the signal power at the filter output is concentrated here. Thus, the QFC Q is determined as follows

$$Q = \frac{f_0}{f_2 - f_1},$$

where f_2, f_1, f_0 - are the right and left cutoff frequencies, respectively, as well as the central frequency of the AFC.

Naturally, the higher the QFC, the steeper the AFC, i.e. rate of rise and fall of the characteristic.

2. Increasing the quality factor characteristic of digital bandpass filters

$$H^2(\varpi) = \frac{(2a_0 \sin(\varpi))^2}{(1 - b_2)^2 + b_1^2 + 2b_1(1 + b_2) \cos(\varpi) + 4b_2 \cos^2(\varpi)}.$$

When connecting bandpass filters of the same type in series, the AFC of the new connection, as noted above, seems to be "compressed", while the cutoff frequencies shift to the central frequency and the steepness of the AFC increases, thereby increasing the QFC of such a connection, Fig. 1 [7].

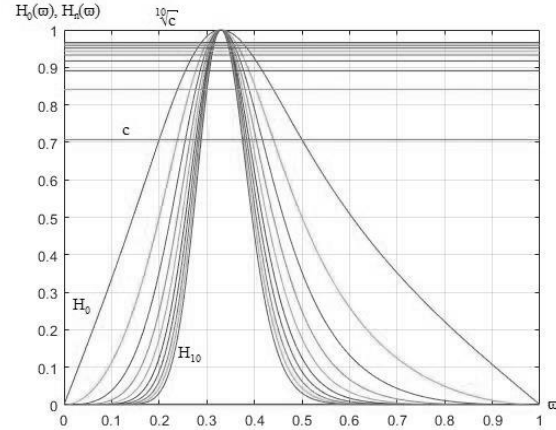


Fig. 1: Amplitude frequency characteristics of digital second-order Butterworth bandpass filters when connected in series.

The transfer function of a basic bandpass filter is mathematically described as follows:

$$H(z) = \frac{a_0 + a_1 z^{-1} + a_2 z^{-2}}{1 + b_1 z^{-1} + b_2 z^{-2}},$$

where a_0, a_1, a_2, b_1, b_2 - the real coefficients of the numerator and denominator, respectively.

When substituting $z^{-1} = e^{-j\varpi}$ or according to Euler's formulas $z^{-1} = \cos(\varpi) - j \sin(\varpi)$, ϖ - where is the normalized angular frequency, $\varpi = 2\pi \frac{f}{f_d}$,

$\varpi \in [0, \pi]$, f, f_d - line frequency and sampling frequency, respectively.

Based on this transformation, we obtain a complex transmission coefficient, and on its basis the AFC at $a_2 = -a_0$, $a_1 = 0$ and after the transformation we obtain the squared AFC in the form:

It should be noted that the AFC peak frequency does not change in this case and is determined by the equation, Fig. 3

$$\varpi_p = \arccos\left(-\frac{b_1}{1+b_2}\right).$$

Typically, the level at which the cutoff frequency is determined is $c = \frac{1}{\sqrt{2}} = 0,707$, those $H(\varpi_c) = c$,

where ϖ_c AFC cutoff frequency at the level c .

When multiplying AFC of the same type or raising their power, the level remains the same, but then to determine the cutoff frequencies of the AFC of a new connection, when they are connected in series, it is necessary to extract the root of the corresponding order from the level c those $\sqrt[n]{c}$, Fig. 2. In Fig. 1, these levels are shown by horizontal lines.

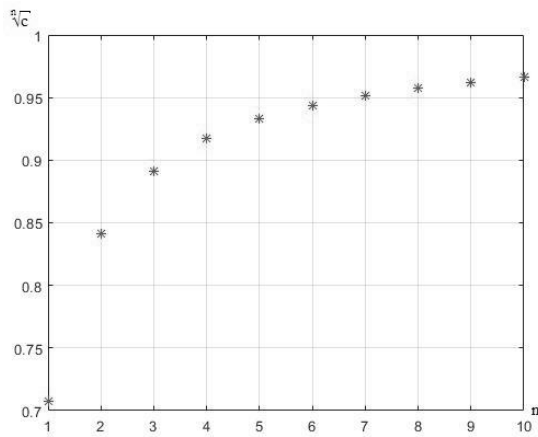


Fig. 2: Graph of the cutoff level depending on the number of connected filters of the same type.

$$H^2(\varpi) = \frac{(2a_0 \sin(\varpi_{1n}))^2}{(1-b_2)^2 + b_1^2 + 2b_1(1+b_2)\cos(\varpi_{1n}) + 4b_2 \cos^2(\varpi_{1n})} = \sqrt[n]{c^2} = c^{\frac{2}{n}}$$

where ϖ_{1n} - cutoff frequency on the new level $\sqrt[n]{c}$ according to the main AFC.

However, when substituting another expression from [7] instead of a_0

$$H^2(\varpi) = \frac{(1-b_2)^2(1-\cos^2(\varpi_{1n}))}{(1-b_2)^2 + b_1^2 + 2b_1(1+b_2)\cos(\varpi_{1n}) + 4b_2 \cos^2(\varpi_{1n})} = c^{\frac{2}{n}}.$$

Introducing a new designation $x = \cos(\varpi_{1n})$ and transforming we obtain a quadratic equation of the form

In this case, using the AFC of the main filter, it can be calculated the cutoff frequencies of the AFC of the new connection. In Fig. 3 shows the correspondence between the cutoff frequencies of the main first-order AFC at level c and the AFC with a series connection of 5 (five) similar first-order AFC. These cutoff frequencies are determined by the main AFC, the parameters of which are known, and by the new level.

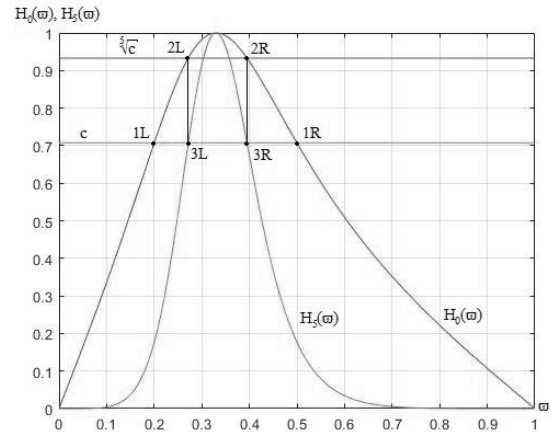


Fig. 3: Amplitude frequency characteristics of the main first-order Butterworth filter and the AFC when five first-order Butterworth filters of the same type are connected in series

To determine the cutoff frequencies of the new AFC after connecting n filters of the same type using the main AFC, it is necessary to solve the equation [10]

$$a_0 = \frac{1-b_2}{2}$$

Instead of $\sin(\varpi_{1n})^2 = 1 - \cos^2(\varpi_{1n})$ obtain

$$\left[4b_2c^{\frac{2}{n}} + (1-b_2)^2 \right] x^2 + 2b_1(1+b_2)x + \left[c^{\frac{2}{n}}b_1^2 + (1-b_2)^2(c^{\frac{2}{n}} - 1) \right] = 0.$$

By solving this equation, we will find formulas for determining the cutoff frequencies for the n th connection of filters of the same type. To simplify the presentation of the result, introduce new notations

$$A = 4b_2c^{\frac{2}{n}} + (1-b_2)^2;$$

$$B = -b_1(1+b_2)c^{\frac{2}{n}};$$

$$C = (1-b_2)\sqrt{(1-c^{\frac{2}{n}})\left[(4b_2-b_1^2)c^{\frac{2}{n}} + (1-b_2)^2\right]};$$

As a result, obtain the cutoff frequencies of the AFC for the n -th connection of filters of the same type, Fig. 4

$$\omega_{cn1} = \arccos\left(\frac{B+C}{A}\right);$$

$$\omega_{cn2} = \arccos\left(\frac{B-C}{A}\right);$$

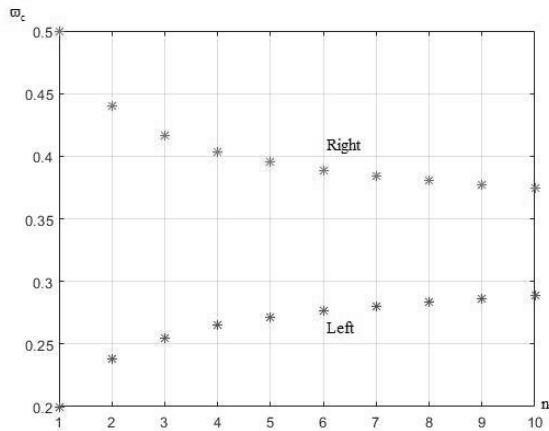


Fig. 4: Graph of cutoff frequencies when connecting filters of the same type in series versus the number of connections.

In accordance with the formulas obtained, it is possible to determine the bandwidth of such a connection as $\omega_{BP} = |\omega_{cn1} - \omega_{cn2}|$, Fig. 5.

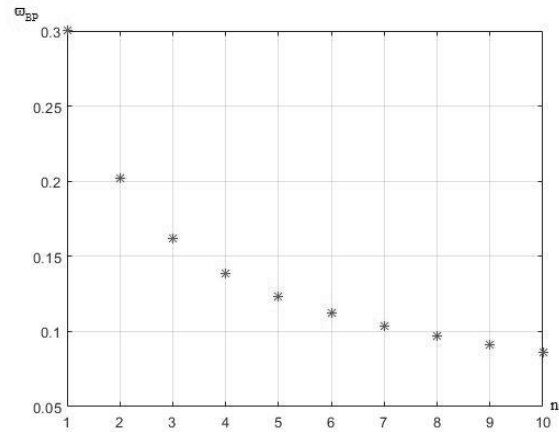


Fig. 5: Graph of bandwidth ω_{BP} versus number of connections.

As can be seen from Fig. 5, the bandwidth decreases exponentially. In this case, it is possible to show how many times the bandwidth of a serial connection will decrease, and therefore the QFC of such a connection will increase, Fig. 6, 7.

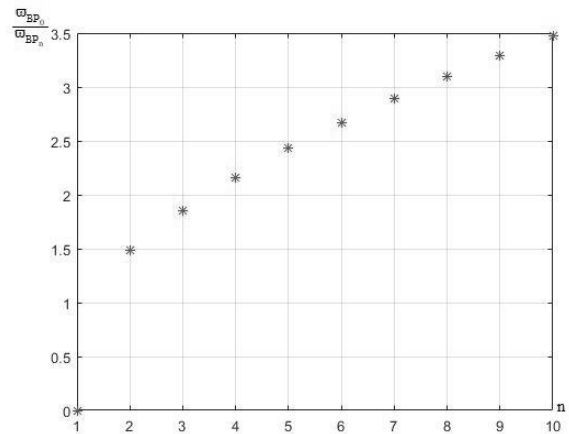


Fig. 6: Graph of bandwidth reduction ω_{BP} versus number of connections.

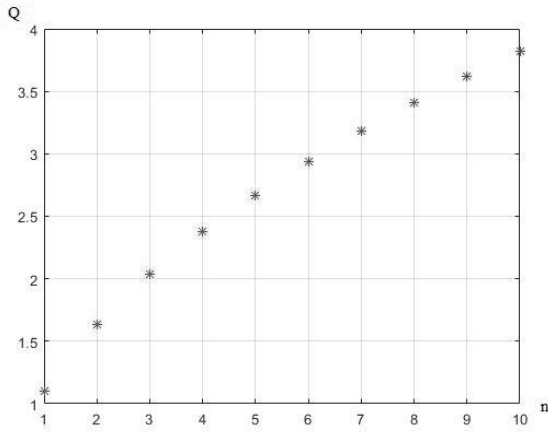


Fig. 7. Graph of quality factor characteristic Q versus connection number.

For example, when connecting four components of the same type, the bandwidth is reduced by more than two times, and with eight, by more than three times, and with ten, the bandwidth is reduced by 3.5 times. At the same time, the QFC increases accordingly by 2.4 times - 3.4 times - 3.8 times.

4. Implementation of this approach

This approach can be implemented digitally in both hardware and software. The hardware implementation is based on the serial connection of n similar components.

The main component is calculated based on data flow information and operating modes. This determines, for example, the cutoff frequencies and bandwidth, as well as the gain. After this, you can implement the block diagram shown in Fig. 8.

$$y_n = a_0^i x_n + ia_0^{i-1} a_1 x_{n-1} + \frac{i!}{2^{i-2}} a_0^{i-2} a_1^2 x_{n-2} + ia_0^{i-3} a_1^3 x_{n-3} + a_1^i x_{n-4} - b_1 y_{n-1} - \frac{i!}{2^{i-2}} b_1^2 y_{n-2} - ib_1^3 y_{n-3} - b_1^4 y_{n-4},$$

where a_i and b_i - coefficients of the numerator and denominator of the first order, respectively, i - number of connected first order components, $i = 1, 2, 3, 4$.

Such an algorithm was implemented, but turned out to be difficult to implement and operate. It required additional calculations, although some of the coefficients of this algorithm were calculated in advance and stored in memory.

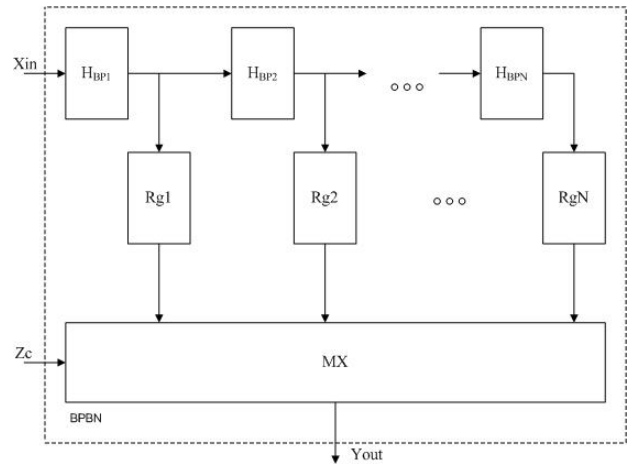


Fig. 8: Block diagram of serial connection of similar components.

The circuit designated as BPBN considers the sequential connection of several H_{BPi} filters of the same type at the same time and the Rg_i registers at the outputs of these components. The MX switch switches the register outputs to the device output. This allows you to reduce the time for re-switching filters and the transient process time, since the necessary data is already in the registers. Such an implementation can be implemented on an FPGA.

The software implementation was used to process data from an ultrasonic obstacle sensor in AMRP based on similar first-order components.

For this purpose, a generalized n -th order algorithm of the form

For the ATMEL MEGA128 microcontroller, an algorithm was developed and a data processing program was written according to a different principle. This made it possible to reduce the hardware of the system, since all sensors are connected to the ADC, which is located in the microcontroller, and also to reduce the processing time of data from the ADC because it is located on the same data bus with the processor.

The signal graph of a first-order bandpass filter is shown in Fig. 9.

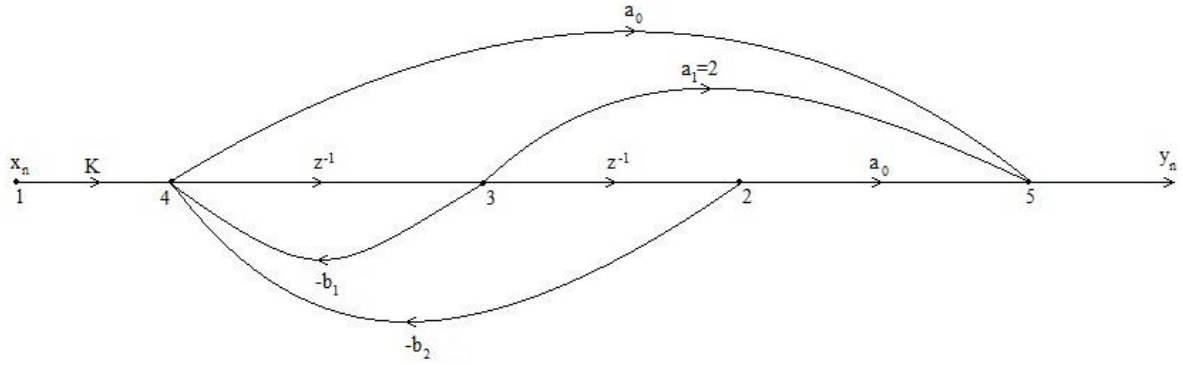


Fig. 9: Signal graph of a first-order digital bandpass filter

Based on the signal graph, a system of equations for the state of the units of the ordered signal graph has been compiled, according to which the calculation algorithm has been compiled:

$$\begin{cases} x_1[i] = x_n(i); \\ x_2[i] = x_3[i-1]; \\ x_3[i] = x_4[i-1]; \\ x_4[i] = kx_i[i] - b_1x_3[i] - b_2x_2[i]; \\ x_5[i] = a_0 * \{x_4[i] + x_2[i]\} + 2x_3[i]; \\ y_n(i) = x_5[i]; \end{cases}$$

where $x_n, x_i[i], y_n$ - respectively, the input sequence, the state of the graph unit, and the output sequence.

This solution is more convenient to implement and operate, which reduced computation time,

$$H(\omega) = \sqrt{\frac{(a_1 + 2a_0 \sin(\omega))^2}{(1 - b_2)^2 + b_1^2 + 2b_1(1 + b_2) \cos(\omega) + 4b_2 \cos(\omega)^2}}$$

As the AFC expands, its steepness also increases with the expansion of the frequency band cut out from the signal spectrum, Fig. 10.

This is not convenient in some objectives, since as the order increases, it is necessary to narrow the cutting band with an increase in the steepness of the AFC.

Then can offer another solution. Form a notch filter based on a bandpass filter in this way

$$H_{SB}(z) = 1 - H_{BP}(z) \quad (1)$$

where, respectively, the transfer function of the notch filter $H_{SB}(z)$ and the bandpass filter $H_{BP}(z)$.

since some constants were calculated in advance and stored in memory cells. In addition, subprograms were written that were run when it was necessary to increase the filter order and the steepness of the AFC.

5. Application of this approach to notch filters

Bandpass filters also include notch filters, which do not pass the necessary frequencies, but cut them out. By analogy with bandpass filters, in this case there will be compression of the AFC. But when connected in series, the AFC of notch filters does not narrow, but expands in accordance with the transfer function of this filter.

$$H(z) = \frac{a_0 + a_1z^{-1} + a_0z^{-2}}{1 + b_1z^{-1} + b_2z^{-2}}$$

The mathematical description of the AFC of a notch filter looks like this.

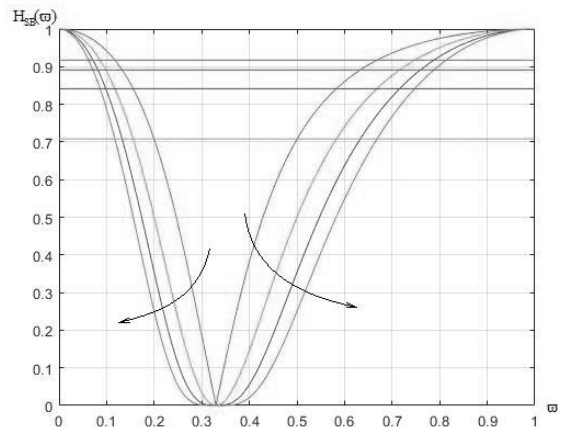


Fig. 10: AFC of first-order digital notch Butterworth filters when connected in series.

In this case, the notch filter will be compressed when low-order bandpass filters are connected in series, Fig. 11.

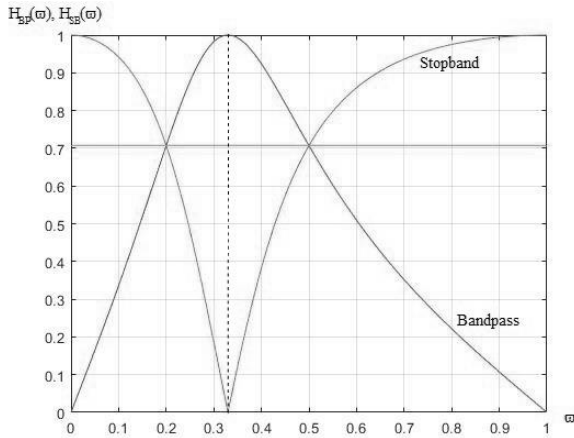


Fig. 11: AFC of a first-order digital notch Butterworth filter obtained from a Butterworth bandpass filter.

Based on this ratios, it is first necessary to find the corresponding bandpass filter from a series connection of the same type, and then, in accordance with formula (1), obtain a notch filter, Fig. 12-13.

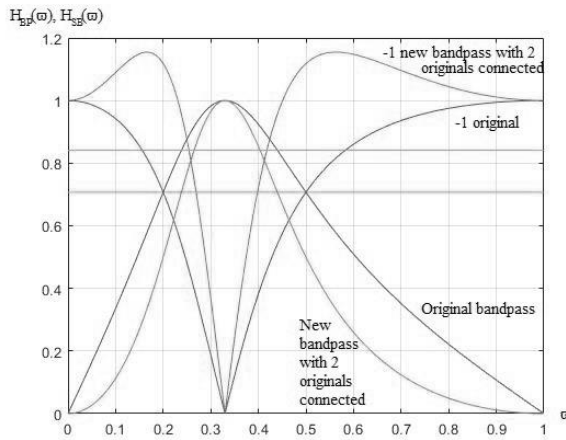


Fig. 12: Amplitude frequency characteristics of a first-order digital notch Butterworth filter obtained from a Butterworth bandpass filter when two similar filters are connected in series.

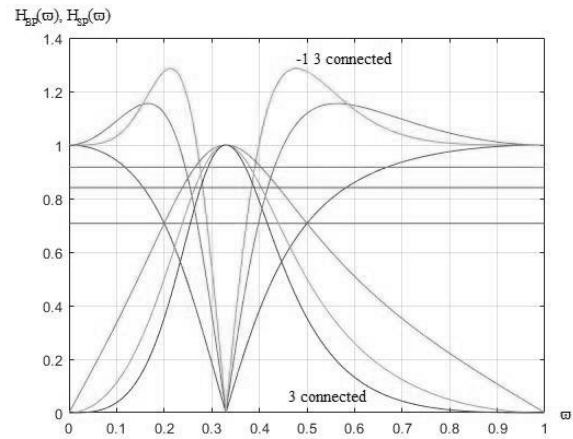


Fig. 13: Amplitude frequency characteristics of a first-order digital notch Butterworth filter obtained from a Butterworth bandpass filter when three filters of the same type are connected in series Other remains the same as in Fig. 12.

6. Implementation of this approach for notch filters

This approach for notch digital filters can be implemented based on the hardware implementation shown in Fig. 8.

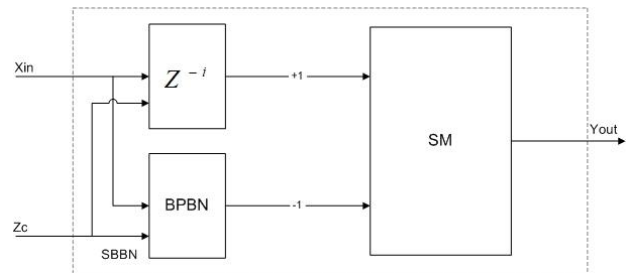


Fig. 14: Block diagram of the implementation of a serial connection of similar components for notch filters.

In Fig. 14 block BPBN is an implementation of Fig. 8. In this block, a series connection of bandpass filters of the same type is implemented, and then ratio (17) is implemented on the adder. The Z^{-1} delay block provides time alignment of the X_{in} signal between blocks. In general, such a block can be called SBBN by analogy.

In addition to hardware implementation, this task can also be implemented in software.

Conclusion

Thus, the analysis showed that the series connection of the same type of bandpass filters makes it possible to increase the QFC of the AFC discretely by an amount equal to the number of connected low-order filters of the same type. Increasing the QFC leads to an increase in the steepness of the characteristic, "compression" of the AFC and narrowing of the bandwidth. Based on the analysis, new formulas were obtained for accurately calculating new cutoff frequencies. This allows quickly calculate the required discrete "compression" of the AFC, and with limited computing capabilities on board the AMRP, use preliminary calculations in the form of tables of values. This approach makes it possible to automatically increase the security of sensor signal processing in the presence of interference.

In addition, the analysis showed that series connection of notch filters does not allow obtaining a similar result for signal processing in order to cut out unwanted frequencies in a narrow frequency band. As shown, this does not result in a narrowing of the cut band, but rather a spread of the band, which is not desirable in such systems.

Another approach based on bandpass filters is proposed to obtain a notch filter, which, when connected in series with bandpass filters, is compressed with an increase in the steepness of the AFC and an increase in the QFC of the filter.

The research also shows that with such a connection the central frequency does not change. It remains in its place, and the cutoff frequencies (left and right) shift to the center.

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ПІДВИЩЕННЯ ДОБРОТНОСТІ ШЛЯХУ ОБРОБКИ СИГНАЛІВ ЦИФРОВОГО ДАТЧИКА В АВТОНОМНИХ МОБІЛЬНИХ РОБОТИЗОВАНИХ ПЛАТФОРМАХ З ОБМЕЖЕНИМИ ОБЧИСЛЮВАЛЬНИМИ РЕСУРСАМИ

Т. В. Ситніков¹

¹Національний університет «Одеська політехніка»,

Анотація. У роботі розглядається проблема побудови автономної мобільної роботизованої платформи з можливістю перебудови їх характеристик залежно від умов експлуатації. Запропоновано новий підхід до розрахунку параметрів нового з'єднання з послідовним з'єднанням однотипних компонентів низького порядку. Отримане співвідношення дозволяє точно розрахувати частоти n -го з'єднання однотипних компонентів. Таке підключення дозволяє підвищити добротність амплітудно-частотної характеристики та зменшити смугу пропускання в 3 рази при восьми підключених однотипних фільтрах. Розглядаються смугові фільтри та режекторні фільтри Баттерворта. Описано поведінку АФС для послідовного підключення.

Ключові слова: амплітудно-частотна характеристика, фазочастотна характеристика, промисловість 4.0-6.0, цифровий фільтр, смуговий фільтр, режекторний фільтр, добротність характеристики, частотно-залежний компонент, режекторний фільтр на основі смугового фільтра, послідовне з'єднання.

Отримано 29.01.2024



Ситніков Тихон Валерійович, Національний університет «Одеська політехніка», аспірант кафедри комп'ютерних систем. Просп. Шевченка, 1, Одеса, Україна, E-mail: tykhon.sytnikov@gmail.com, тел. +38-048-705-84-54

Tykhon Sytnikov, Odesa Polytechnic National University, post-graduate student of the Computer Systems department, Shevchenko ave., 1, Odessa, Ukraine

ORCID ID: 0000-0002-0137-5643