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SINGLE-FREQUENCY FILTER FOR SIGNAL PROCESSING

Abstract. Modern methods of band-stop filtering are sensitive to the influence of high-frequency single-frequency interference, which significantly distorts the shape of the informative signal. The noted feature is leveled by the system of narrow-band high-Q band-stop filtering developed in the article. The narrow-band high-Q band-stop filter is approximated by the Butterworth polynomial of the second degree and has the property of a closed circuit of the negative feedback loop, which, unlike the existing system, ensures high-precision processing of noisy measurements. The choice of this second-degree polynomial is justified by its maximally flat and symmetrical amplitude-frequency characteristic, the absence of pulsations in the interference suppression band and signal transmission, as well as the allocation of the lowest distortion for the selected order. The article under consideration presents the result of synthesis of a control system for a narrow-band high-Q band-stop filter with a variation of the correction coefficient of the feedback loop, which increases the efficiency of processing noisy measurements when introducing a value for this coefficient K = 0.1. It was revealed that the smallest value of this coefficient, compared to the value obtained when forming single feedback, significantly increases the value of the filter gain on its frequency response and thereby ensures narrowing of the suppression band to increase the quality factor of the rejection filter at the interference frequency. Moreover, a non-random and significant correlation relationship was found between the measured indicators, caused by a decrease in the accuracy and noise immunity indicators of the signal processing system with an increase in the values of the correction coefficient of the feedback loop of the rejection filter of the selected order. At the same time, understanding the discovered relationship used in developing a method for processing noisy measurements will significantly improve the accuracy and noise immunity of the signal processing system. The presented results, characterizing a statistically significant and non-random relationship, confirm the operability and functioning of the signal processing system, which determines the operation of a high-quality rejection filter when filtering single-frequency interference.
Keywords. Filter, signal processing, feedback control, accuracy, noise resistance.

Introduction. Today, the development of new and robust methods for rejection filtering against high-frequency interference is a pressing issue in the processing of measurement information. This relevance stems from the fact that such filters largely allow their parameters [1-4] to be adjusted to those of the processed signals when isolating the informative components of the signal from an additive mixture of high-frequency and single-frequency narrowband interference. Interference with such frequency content is primarily induced by the electrical network [5,6] when connecting external high-frequency devices [4] and various motors [7,8]. The presence of interference in signal information can significantly affect the measurement accuracy of the signal component, which can only be improved through the use of filtering methods [2,4,9].

Among the filtering methods, not only notch filters but also low-pass filters [10] are capable of filtering this interference. Unlike notch filters, low-pass filters, due to the characteristics they impart when filtering interference, are capable of smoothing the amplitude of the information signal, which is mainly due to the type of placement of the root loci-zeros and poles and their distance from each other on the complex plane. Consequently, a notch filter on the complex plane localizes the root loci-poles and zeros-rather close to each other due to the presence of the parameter $s^2 + \omega^2$ in the numerator of the continuous transfer function of this filtering element [3].

The frequency response of a band-stop filter is approximated in the vast majority of cases using polynomial models [2-4], which allow one to achieve the required form of the amplitude-frequency response for solving the signal processing problem. Among the well-known and widely used polynomial models for approximating the frequency response are those based on the Butterworth, Bessel, Chebyshev, Newton, and Cauer polynomials [2-4,9]. The listed polynomial models allow one to obtain a clearly distinguishable frequency response of the filter [10], which affects the efficiency of signal processing when filtering out the interference signal. Due to the use of the listed polynomial models for approximating the frequency response, the class of these methods is usually called the Butterworth, Bessel, Newton, Chebyshev, and Cauer polynomial filters [10].

According to the research data on notch filters [2, 11-14], among the listed methods of notch filtering, the filter approximated by the Butterworth polynomial provides high accuracy of signal processing. This is mainly due to the low values of signal processing accuracy and the generation of the largest values of the intrinsic error of these filters associated with their frequency characteristics, the noise stop band and the quality factor Q of the notch filter. In addition, the quality factor also has a significant impact on the accuracy of processing during signal measurement and the value of this indicator can be low only in the case [2] when the noise stop band is expanded. In the works [10], it was identified and established that two approaches are mainly used for the synthesis of notch filters using polynomial models.

The first approach is based on the use of a stop-band of interference B, while the value of the quality factor Q of the filter under consideration is inversely proportional to this indicator. Consequently, the efficiency of signal processing at the output of such a system under the influence of single-frequency narrow-band interference will be insufficiently high [2]. In addition, this approach to the synthesis of a rejection filter is accompanied by a doubling of the filter order, which may be a characteristic process in the production of band-pass filters and band-stop polynomial continuous filters [10]. It is important to emphasize that in this approach, when using an approximating first-degree polynomial n=1 for synthesis, the order of the filtering system is equal to two, that is, n=2, which leads to a change in the characteristics of the filters and is considered a feature of this approach.

The second approach is based on a parallel connection of the transfer functions of high-pass and low-pass filters (HPF and LPF), where the lower filter notch boundary is characterized by the cutoff frequency ω_1 for the HPF and the upper cutoff frequency ω_2 for the LPF. The overall transfer function $W(s)$ of such a notch filter is calculated by adding the two transfer functions of the HPF and LPF. This approach differs from the first in that, instead of the interference stop-band B, the cutoff frequencies ω_1 and ω_2 are used, defining the rejection width of a single-frequency interference variable over a specific frequency range.

In [2], building on approach 2, a new single-frequency notch filter is synthesized. This filter is based on a second-degree Butterworth polynomial and is characterized by high filtering efficiency for noisy signals and accuracy compared to the Daubechies filter [11,15]. The key characteristic of the synthesized new notch filter is its high frequency quality factor, as well as its uniform frequency response, which has a positive effect on the efficiency of signal processing.

However, despite the noted superiority of the synthesized notch filter [2] over the Daubechies filter [11,15], the question of its further development by forming a feedback loop to correct its frequency response is currently considered open. Solving this processing problem is necessary to increase the gain on the filtering system's frequency response, which is inevitably reduced by forming a single-feedback loop. Therefore, synthesizing the overall transfer function of a notch filter with negative feedback to evaluate the effect of the correction coefficient on the frequency response for this element is a relevant and fundamental problem requiring a comprehensive approach.

In contrast to [2-4], this article presents the results of an assessment of signal processing accuracy by analyzing the effect of the feedback loop's correction coefficient on the frequency response of a single-frequency notch filter.

Materials and research methods. The synthesis method is based on the mathematical apparatus of transfer functions of continuous analog filters in a normalized frequency range, allowing the synthesis of high- and low-pass filters, where the resulting general transfer function for a single-frequency rejection filter is obtained by adding two filter circuits of the signal processing system, which has the form:

$$\begin{cases} W_{1\_\text{ФНЧ}}(s) = W_{\text{нормированый}}(s)\Big|_{s \to \frac{s}{\omega_C}} = \dfrac{1}{\left(\frac{s}{\omega_C}\right)^2 + 1{,}414\frac{s}{\omega_C} + 1} = \\ \dfrac{1}{\frac{s^2 + 1{,}414\omega_C s + \omega_C^2}{\omega_C^2}} = \dfrac{\omega_C^2}{s^2 + 1{,}414\omega_C s + \omega_C^2} \end{cases} \quad (1)$$

$$\begin{cases} W_{2\_\text{ФВЧ}}(s) = W_{\text{нормированный}}(s)\Big|_{s \to \frac{\omega_c}{s}} = \dfrac{1}{\left(\frac{\omega_c}{s}\right)^2 + 1{,}414\frac{\omega_c}{s} + 1} \\ = \dfrac{1}{\frac{s^2 + 1{,}414\omega_c s + \omega_c^2}{s^2}} = \dfrac{s^2}{s^2 + 1{,}414\omega_c s + \omega_c^2}. \end{cases} \quad (2)$$

The general transfer function W(s) of a single-frequency notch filter is:

$$W(s) = W_1(s) + W_2(s) =$$
$$= \frac{s_c^2}{s^2 + 1{,}414\omega_c s + \omega_c^2} + \frac{\omega_c^2}{s^2 + 1{,}414\omega_c s + \omega_c^2} = \frac{s_c^2 + \omega_c^2}{s^2 + 1{,}414\omega_c s + \omega_c^2} \quad (3)$$

The control system for the synthesized general transfer function of the notch filter is implemented by adding negative feedback with a correction coefficient K, variable in the range $0.1<K<1.0$, respectively. The transfer functions of a single-frequency notch filter with a second-degree Butterworth polynomial with coefficient K are as follows:

$$\begin{cases} W_{\text{общ}\_K=0,1}(s) = \dfrac{10s^2 + 10\omega_c^2}{11s^2 + 1{,}414\omega_c s + 11\omega_c^2} \\ W_{\text{общ}\_K=0,2}(s) = \dfrac{5s^2 + 5\omega_c^2}{6s^2 + 1{,}414\omega_c s + 6\omega_c^2} \\ W_{\text{общ}\_K=0,3}(s) = \dfrac{10s^2 + 10\omega_c^2}{13s^2 + 4{,}242\omega_c s + 13\omega_c^2} \\ W_{\text{общ}\_K=0,4}(s) = \dfrac{5s^2 + 5\omega_c^2}{7s^2 + 2{,}828\omega_c s + 7\omega_c^2} \\ W_{\text{общ}\_K=0,5}(s) = \dfrac{2s^2 + 2\omega_c^2}{3s^2 + 1{,}414\omega_c s + 3\omega_c^2} \\ W_{\text{общ}\_K=0,6}(s) = \dfrac{5s^2 + 5\omega_c^2}{8s^2 + 4{,}242\omega_c s + 8\omega_c^2} \\ W_{\text{общ}\_K=0,7}(s) = \dfrac{10s^2 + 10\omega_c^2}{17s^2 + 9{,}898\omega_c s + 17\omega_c^2} \\ W_{\text{общ}\_K=0,8}(s) = \dfrac{5s^2 + 5\omega_c^2}{9s^2 + 5{,}656\omega_c s + 9\omega_c^2} \\ W_{\text{общ}\_K=0,9}(s) = \dfrac{10s^2 + 10\omega_c^2}{19s^2 + 12{,}726\omega_c s + 19\omega_c^2} \\ W_{\text{общ}\_K=1}(s) = \dfrac{s^2 + \omega_c^2}{2s^2 + 1{,}414\omega_c s + 2\omega_c^2} \end{cases} \quad (4)$$

The properties of a synthesized second-order notch filter control system are assessed in two stages: direct and indirect parameters at a normalized cutoff frequency of ω = 1 rad/s [10]. The indirect parameters are the amplitude-frequency response (AFR) and root-square characteristic, while the direct parameters are the filter's transient response. These parameters are considered informative for identifying the internal processes occurring within the filtering system's structure.

A relationship illustrating the influence of the feedback loop correction coefficient is demonstrated using a linear regression analysis method, which allows one to determine the strength of the relationship between the evaluated parameters [16], calculated at the output of the synthesized notch filtering system. The parameters used in the evaluation were those that most fully characterize the filtering system's performance when solving a signal processing problem.

The closeness, strength, and direction of the estimated relationship between the correction coefficient and the indicators are determined using the Chaddock scale and characterized as follows: $0.9<r<1.0$ – very high (strong) relationship, $0.7<r<0.9$ – high relationship, $0.7<r<0.5$ – noticeable relationship, $0.5<r<0.3$ – moderate relationship, $0.3<r<0.1$ – weak relationship. The non-randomness of the resulting relationship between the indicators is characterized by the p-level of significance, where the threshold level for accepting the hypothesis of a significant relationship is $p = 0.05$, respectively.

Research results. The results obtained after substituting (1) and (2) the value ω=1 rad/second into the overall $W(s)$ transfer function (3) of the notch filter with feedback (4) for $0.1<K<1.0$, made it possible to study the endowed properties illustrated in Figure 1. In this case, Figure 1 shows, for clarity, the filter characteristics calculated for the values of the contour coefficient K=0.1, K=1.0 and without feedback ($W(s)$ for comparison purposes) from all the analyzed frequency characteristics of the filters for $0.1<K<1.0$.

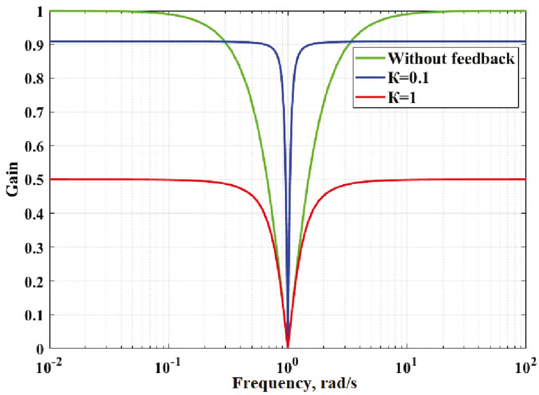

Figure 1 – Effect of the feedback loop correction coefficient on the frequency response of the notch filter

From the figure, it's easy to see that the notch filter with a K=0.1 correction factor in the feedback loop has a gain of 0.9 in the frequency response, while for K=1.0, the gain in the frequency response is 0.5. Furthermore, the filter gain of 0.9 achieved with K=0.1 is 1.8 times greater than the gain of 0.5 achieved with K=1.0 (unity negative feedback), respectively.

Furthermore, if we compare the filter frequency response characteristics, we can see that the frequency response with K=0.1 has a steeper roll off than with K=1.0 and without a feedback loop. However, a notch filter without feedback, compared to K=0.1 and K=1.0, has a frequency response gain of unity and a wide rejection band. Given a wider rejection band, this will result in a low Q factor and can significantly impact signal processing efficiency. Therefore, for a more thorough understanding and description of these effects, Table 1 presents the results of evaluating the properties of notch filters.

Table 1 – Evaluation of direct and indirect indicators of the filtration system

0,1<K<1,0	Direct and indirect indicators		
	Zeros	Poles	Transient time, s
0,1	-0±1i	-0,064±0,998 i	61,7
0,2		-0,118±0,993 i	33,7
0,3		-0,163±0,987 i	24,4
0,4		-0,202±0,979 i	20,8
0,5		-0,236±0,972 i	18,0
0,6		-0,265±0,964 i	15,3
0,7		-0,291±0,957 i	14,9
0,8		-0,314±0,949 i	12,5
0,9		-0,335±0,942 i	12,4
1,0		-0,353±0,935 i	12,2
W(s)	-0±1i	-0,707±0,707 i	7,0

The presented filter property assessment shows that, due to the decrease in the feedback correction coefficient of the rejection filters, the poles move closer to the imaginary axis (i), thus increasing the transient time. The distance between the pole and the imaginary axis for K=0.1 is only 0.002 units, while for a filter with K=1.0, this distance is 0.065 units, which provokes the formation of a long transient process with a time of t_p=61.7 s at K=0.1 compared to the filter without feedback and the filter with K=0.1, according to the assessment presented in Figure 2.

Moreover, the smallest distance between the pole and the imaginary axis of the notch filter at K=0.1 on the frequency response (Figure 3) produces a steeper roll-off and a narrow filter noise suppression band, which makes it possible to obtain a high-Q notch filter that affects the signal processing and the fulfillment of the condition for minimizing the error $e(t)$ of the measurement estimate. Moreover, the formed distance of 0.293 units between the pole and the imaginary axis for a single-frequency Butterworth notch filter without feedback, in contrast to the notch filters with feedback under consideration, generates a gain on the frequency response equal to 1. Thus, the differences in the characteristics provide a complete basis for stating the identified features of the synthesized filters, taking into account the influence of the correction coefficient of the feedback loop at $0.1<K<1.0$ on the quality indicators of the system during signal processing.

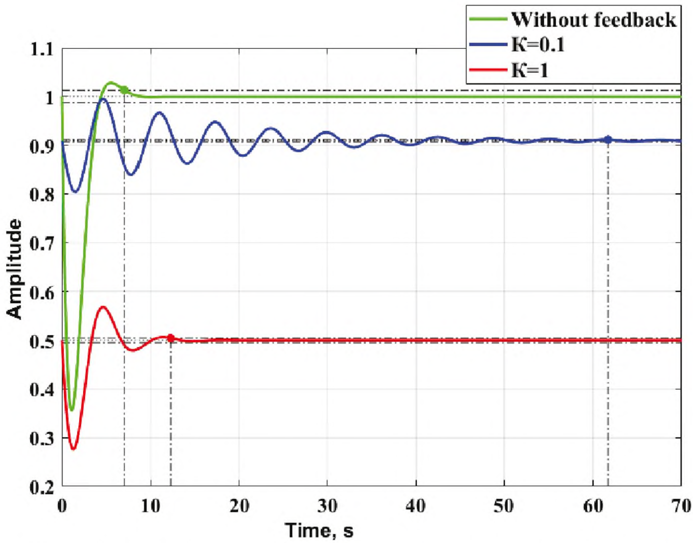

Figure 2 – Effect of the feedback loop correction coefficient on the transient response of the notch filter

In order to obtain the results of signal processing, the additive model of sinusoidal signals and its rejection filtering has the form as shown in Figure 3 for a filter with K=0.1.

From the above notch filtering result for K=0.1, it follows that the synthesized notch filter can filter out single-frequency interference of ω=1 rad/s and isolate the signal's information component similar to that of the noise-free reference signal. The introduced distortion in the form of undamped oscillations for this filter should be considered inherent to this process, caused by the close proximity of the system's poles to the imaginary axis. This leads to the emergence of a long-term transient process, which also affects the signal $e(t)$ of the measurement estimation error, shown in Figure 4.

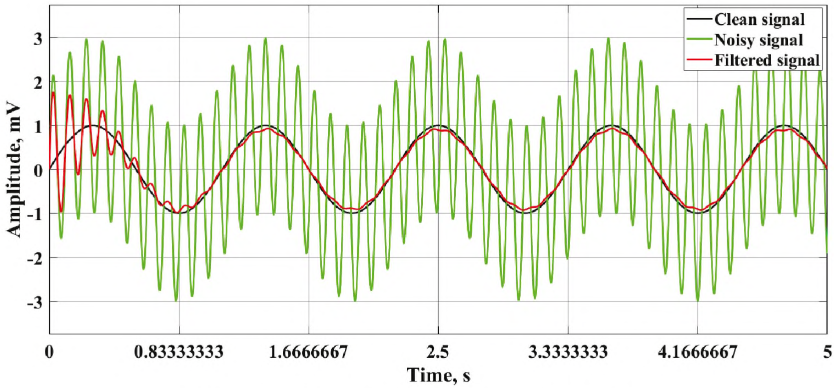

Figure 3 – Notch filtering of sinusoidal signals

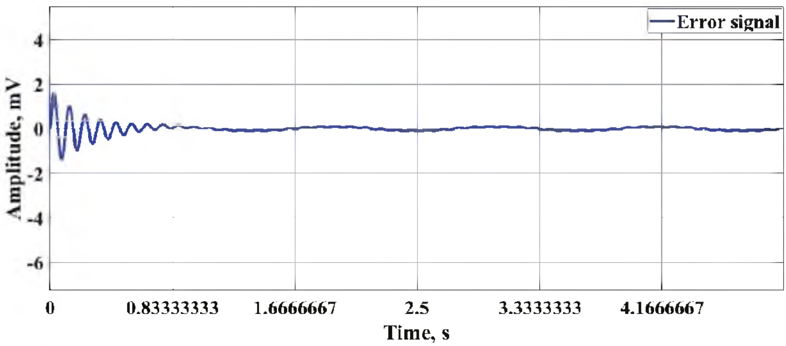

Figure 4 – Measurement estimation error

From the presented assessment it follows that the notch filter at K = 0.1 ensures the minimization of the measurement error of the signal components, converging to zero, and allows us to state an increase in the measurement accuracy of the components of the signal *s*(*t*) under consideration. However, in order to speak about the increase in accuracy, there is a great need to conduct a quantitative assessment of such indicators that can most fully characterize the operation of the signal processing system. Such indicators can be the signal-to-noise ratio (SNR), the root-mean-square deviation (MSE), calculated between the readings of the reference and filtered noisy signal, adapted from [16]. The results of the indicator assessment are presented in Table 2.

Table 2 – Evaluation of signal processing efficiency

0,1<*K*<1	Direct and indirect indicators		
	SNR_before, dB	SNR_after, dB	MSE, mV
0,1	0,969	12,250	$4{,}795 \cdot 10^{-4}$
0,2		11,732	$4{,}986 \cdot 10^{-4}$
0,3		9,602	$5{,}633 \cdot 10^{-4}$
0,4		7,543	$6{,}616 \cdot 10^{-4}$
0,5		5,778	$7{,}555 \cdot 10^{-4}$
0,6		4,276	$8{,}412 \cdot 10^{-4}$
0,7		2,979	$9{,}185 \cdot 10^{-4}$
0,8		1,844	$9{,}879 \cdot 10^{-4}$
0,9		0,835	$1 \cdot 10^{-3}$
1,0		-0,069	$1{,}1 \cdot 10^{-3}$

The presented assessment shows that a Butterworth notch filter with K=0.1, compared to K=1.0, provides high measurement accuracy (MSE) and SNR of processed signals to single-frequency interference. It should also be noted that the lowest MSE value indicates similarity between the filtered signal and the reference signal.

The impact of the correction coefficient 0.1<K<1.0 of the notch filter's negative feedback loop on signal processing performance can also be determined using a linear regression analysis of the parameters. For this analysis, the K coefficient values should be selected as the predictor, and the SNR and MSE parameters should be the focus variables of the study. The results of the analysis can be visualized using a scattergram, with the paired correlation and determination coefficients calculated, as shown in Figure 5.

The results presented in Figure 5 demonstrate a close, linear relationship between the SNR, MSE, and K, characterizing the influence of K on the performance of the signal processing system. A non-random negative correlation was found between the SNR and K at r = -0.991, R^2 = 0.982, and $p = 2 \cdot 10^{-7}$, indicating a decrease in the SNR with increasing K. A direct, non-random relationship was found between the MSE and K at r = 0.993, R^2 = 0.986, and $p = 1 \cdot 10^{-7}$, characterizing an increase in filtering error due to an increase in K. Thus, the results of the relationship assessment obtained through linear regression analysis are consistent with the data presented above.

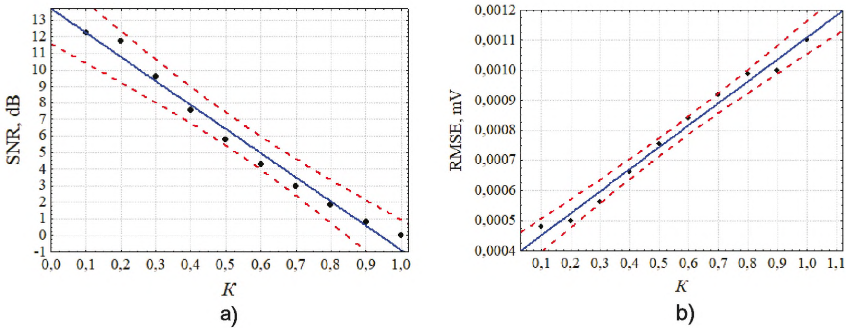

Figure 5 – Dependence of the influence of the feedback loop correction coefficient on the signal processing quality indicators: a) SNR – the ratio of the filtered sinusoidal signal to the single-frequency interference; b) MSE – the standard deviation of the signal processing results between the test and filtered signals

The scientific novelty of this research result lies in the established relationship between the SNR and the MSE of the signal-to-noise ratio and the values of the correction coefficient of the negative feedback loop of the notch filter:

- changing the coefficient values in the range from 0.1 to 1.0 changes the signal-to-noise ratio; further increasing this value leads to a decrease in the effectiveness of processing noisy measurements in terms of noise immunity;

- decreasing the correction coefficient of the feedback loop by 0.1 narrows the single-frequency interference suppression band in the internal structure of the system, thereby increasing the frequency quality factor of this filter and the effectiveness of processing noisy measurements in terms of accuracy by $4.795 \cdot 10^{-4}$ mV and noise immunity by 12 dB.

Conclusion. This article presents new performance evaluation results for a previously developed single-frequency notch filter based on the Butterworth polynomial. The effect of the negative feedback loop correction coefficient is evaluated for this second-order single-frequency notch filter. It is shown that the Butterworth single-frequency notch filter, with a feedback coefficient of K = 0.1, exhibits a steeper frequency response roll off, the width of which is significantly narrower than that of a filter without feedback. This paper establishes for the first time the influence of the negative feedback loop correction coefficient on the signal processing accuracy and noise immunity of a Butterworth single-frequency notch filter by an average of 12.250 dB with a non-random inverse correlation coefficient of 0.991, respectively.

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СИГНАЛДАРДЫ ӨҢДЕУГЕ АРНАЛҒАН БІР ЖИІЛІКТІ СҮЗГІ

Түйіндеме. Қазіргі таңда қолданысқа ие болып келетін режекторлық сүзгілер бір мәнді жоғары жиілікті шуылды кедергілердің әсеріне өте сезімтал болып келеді. Нәтижесінде өлшенетін сигналдардың формасын бұрмаландырып ауытқуларға ұшыратады. Атап өткен ауытқу түрі қарастыруға ұсынылған мақалада қуыс жолақты бір мәнді жиілігі бар режекторлық сүзгі жүйесімен жойылады. Қуыс жолақты бір мәнді жиілігі бар режекторлық сүзгісінің жиіліктік сипаттамасы екінші дәрежелі Баттерворт көпмүшесімен аппроксимацияланған және құрамында кері байланыспен тұйықталған, ал басқада жүйелермен салыстырғанда шуылы бар өлшеулерді жоғары дәлдікпен өңдейді. Қарастырып отырған сүзгіге екінші дәрежелі көпмүшені таңдау оның максималды тегіс және симметриялы амплитуда жиіліктік сипаттамасымен, шуылдарды сүзгілеу жиілік жолағында лүпілдердің болмауымен және өз ауытқуларын аз мөлшерде бөлуімен негізделген. Жиілік облысындағы қуыс жолақты режекторлық сүзгінің басқару жүйесінің синтезі кері байланыстың коэффициентін коррекциялау диапазонында келтірілген. Осы коэффициенттің мәні К=0,1 болған жағдайда электрлік шуылы бар өлшемдердің өңдеу нәтижелігі жоғарлайтыны толығымен анықталып көрсетілген. Сондай-ақ бұл коэффициентпен режекторлық сүзгінің амплитудалық жиілік сипаттамасында электрлік шуылды сүзгілеу диапазонында қуыс жолақтың пайда болуын қамтамасыз етеді. Сонымен қатар режекторлық сүзгінің беріліс функциясының кері байланыс коэффициентімен коррекциялау мәндерімен сигналдардың өлшеу дәлділігін және шуылға төзімділігін анықтайтын көрсеткіштер арасында кездейсоқ емес корреляциялық байланыс анықталды. Анықталған корреляциялық байланысты шуылы бар өлшемдерді өңдеу әдісін әзірлеу кезінде қарастырып және қолдануға болады. Орнатылған байланысты математикалық статистика тұрғысынан анықтасақ, ол өлшенген сигналдарды өңдеу жүйесінің нәтижелігін толығымен расстайды.

Түйінді сөздер: Сүзгі, сигналдарды өңдеу, басқару, кері байланыс, дәлділік, шуылға төзімділік.

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ОДНОЧАСТОТНЫЙ ФИЛЬТР ДЛЯ ОБРАБОТКИ СИГНАЛОВ

Аннотация. Современные методы режекторной фильтрации чувствительны к влиянию высокочастотной одночастотной помехи, которая оказывает существенное искажение формы информативного сигнала. Отмеченная особенность нивелируется путем разработанной в статье системы узкополосной высокодобротной режекторной фильтрации. Узкополосный высокодобротный режекторный фильтр аппроксимирован полиномом Баттерворта второй степени и обладает свойством замкнутой цепи контура отрицательной обратной связи, что, в отличие от существующей системы, обеспечивает высокоточную обработку зашумленных измерений. Выбор данного полинома второй степени обоснован его максимально плоской и симметричной амплитудно-частотной характеристикой, отсутствием пульсаций на полосе подавления помехи и пропускания сигнала, а также наделением наименьшего искажения для выбранного порядка. В рассматриваемой статье представлен результат синтеза системы управления узкополосным высокодобротным режекторным фильтром при вариации корректирующего коэффициента контура обратной связи, повышающий результативность обработки зашумленных измерений при введении значения для данного коэффициента K = 0,1. Выявлено, что наименьшее значение данного коэффициента в сравнении со значением, получаемым при формировании единичной обратной связи, существенно повышает значение коэффициента усиления фильтра на его частотной характеристике и тем самым обеспечивает сужение полосы подавления для повышения добротности режекторного фильтра на частоте среза помехи. Более того, обнаружена неслучайная и значимая корреляционная взаимосвязь между измеренными показателями, обусловленная понижением показателей точности и помехоустойчивости системы обработки сигнала при увеличении значений корректирующего коэффициента контура обратной связи режекторного фильтра выбранного порядка. Вместе с тем понимание обнаруженной связи, используемой при разработке метода обработки зашумленных измерений, позволит существенно улучшить точность и помехоустойчивость системы обработки сигнала. Представленные результаты, характеризующие статистически значимую и неслучайную связь, подтверждают работоспособность и функционирование системы обработки сигнала, определяющей работу высокодобротного режекторного фильтра при фильтрации одночастотной помехи.

Ключевые слова. Фильтр, обработка сигнала, обратная связь, точность, помехоустойчивость.

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