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«Central Asian Academic Research Center» LLP is pleased to announce that "News of NAS RK. Series of Geology and Technical sciences" scientific journal has been accepted for indexing in the Emerging Sources Citation Index, a new edition of Web of Science. Content in this index is under consideration by Clarivate Analytics to be accepted in the Science Citation Index Expanded, the Social Sciences Citation Index, and the Arts & Humanities Citation Index. The quality and depth of content Web of Science offers to researchers, authors, publishers, and institutions sets it apart from other research databases. The inclusion of News of NAS RK. Series of Geology and Technical Sciences in the Emerging Sources Citation Index demonstrates our dedication to providing the most relevant and influential content of geology and engineering sciences to our community.

«Орталық Азия академиялық ғылыми орталығы» ЖШС «ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Web of Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді геология және техникалық ғылымдар бойынша контентке адалдығымызды білдіреді.

ТОО «Центрально-азиатский академический научный центр» сообщает, что научный журнал "Известия НАН РК. Серия геологии и технических наук» был принят для индексирования в Emerging Sources Citation Index, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Включение Известия НАН РК. Серия геологии и технических наук в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному контенту по геологии и техническим наукам для нашего сообщества.

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PREDICTIVE MODEL FOR ASSESSING DIAGNOSTIC SIGNIFICANT PARAMETERS OF ACOUSTIC EMISSION: MACHINE LEARNING EVIDENCE

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Abstract. *Relevance.* Acoustic emission (AE) systems and complexes offer a sensitive method for determining acoustic stress in rocks and geological fields, and also detecting various defects during selective laser melting of heat-resistant alloys. However, when operating this system, the AE signal recording process is inevitably subject to interference, which can significantly reduce the accuracy of signal parameter measurements. Therefore, to improve the accuracy of AE signal measurement, filtering methods are used to isolate diagnostic parameters from noise. *Objective.* The aim of this study is to improve the accuracy of AE signal parameter estimation by developing a digital filtering method and a phenomenological model of the information component. *Methods.* The proposed bi-directional filtering method for the AE signal model based on Butterworth digital filter is considered. The informative components of the signal are extracted, the parameters are measured and the relative measurement error between the signal models is calculated. Furthermore, at the output of the digital filtering method, the signal-to-noise ratio is computed to determine the association between this indicator and the measurement accuracy of diagnostic AE parameters. The relationship between the indicators is approximated using the least squares method and visualized by a scatterplot, which displays the distribution of data as points along the *x-y* coordinate. *Results and conclusions.* The implementation of the method improves the accuracy of measuring AE parameters, while the relative error does not exceed 3% compared to the Daubechies wavelet filter of the selected order and decomposition level.

Keywords: signal processing, measurement accuracy enhancement, acoustic emission, signal-to-noise ratio, acoustic inspection, noise, Butterworth filter, wavelet filter

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АКУСТИКАЛЫҚ ЭМИССИЯНЫҢ ДИАГНОСТИКАЛЫҚ МАҢЫЗДЫ ПАРАМЕТРЛЕРІН БАҒАЛАУДЫҢ ПРЕДИКТИВТІ МОДЕЛІ: МАШИНАЛЫҚ ОҚЫТУ ДЕРЕКТЕРІ

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Аннотация. *Өзектілігі.* Заманауи акустикалық-эмиссиялық жүйелер мен кешендер – тау жыныстарының акустикалық қасиеттері мен кернеулерін, геологиялық өрістерді, сонымен қатар аддитивті өндіріс өнімдері үшін ыстыққа төзімді қорытпаларды селективті лазерлік балқыту кезінде әртүрлі ақауларды анықтауда сезімтал әдіс болып табылады. Алайда, мұндай жүйелер мен кешендерді пайдалану кезінде акустикалық эмиссияны тіркеу процесіне аддитивті шудың әсерінен туындайтын сыртқы факторлар ықпал етіп, акустикалық сигналдың параметрлерін өлшеу дәлдігін едәуір төмендетуі мүмкін. Акустикалық сигнал параметрлерін өлшеу дәлдігін арттыру үшін шу фонында диагностикалық параметрлерді бөліп көрсетуге арналған әртүрлі цифрлық сүзгілеу әдістері қолданылады. Мақаланың негізгі мақсаты – цифрлық полиномды сүзгілеу әдісін және дәлдікті бағалау үшін ақпараттық құрамдас бөліктің феноменологиялық моделін жасау арқылы акустикалық эмиссия сигналының диагностикалық маңызы бар параметрлерін бағалау дәлдігін арттыру. *Әдістер***.** Екінші ретті Баттерворт цифрлық сүзгісіне негізделген акустикалық эмиссия сигналының моделін екі бағыттағы сүзгілеу әдісін жүзеге асыру қарастырылды. Сигналдың ақпараттық құрамдас бөлігінің формалары алынып, акустикалық эмиссияның диагностикалық параметрлері өлшенді, сигнал модельдері арасындағы салыстырмалы қателіктің пайыздық көрсеткіші анықталды. Сондай-ақ, цифрлық сүзгілеу әдісінің шығысында акустикалық сигнал мен бөгеуілдің қатынасы есептеліп, осы көрсеткіш пен акустикалық эмиссияның диагностикалық параметрлерін өлшеу дәлдігі арасындағы байланыс анықталды. Бұл тәуелділік ең кіші квадраттар әдісін қолдану арқылы аппроксимацияланып, x және y координаталық жазықтықтарындағы нүктелер түріндегі деректерді бейнелеу арқылы шашырау диаграммасы визуализацияланды. *Нәтижелер***.** Ұсынылатын әдісті жүзеге асыру кезінде акустикалық эмиссияның диагностикалық параметрлерін өлшеу дәлдігі артатындығы анықталды. Таңдалған реттілік пен жіктеу деңгейіндегі Добеши вейвлет сүзгісімен салыстырғанда салыстырмалы өлшеу қателігінің мәні 3 пайыздан аспайды.

Түйін сөздер: сигналды өңдеу, өлшеу дәлдігін арттыру, акустикалық эмиссия, сигнал/шу қатынасы, акустикалық бақылау, бөгеуілдер, Баттерворт сүзгісі, вейвлет-сүзгі

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ПРЕДИКТИВНАЯ МОДЕЛЬ ОЦЕНКИ ДИАГНОСТИЧЕСКИ ЗНАЧИМЫХ ПАРАМЕТРОВ АКУСТИЧЕСКОЙ ЭМИССИИ: ДАННЫЕ МАШИННОГО ОБУЧЕНИЯ

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Аннотация. *Актуальность.* Современные акустико-эмиссионные системы и комплексы являются чувствительным методом идентификации акустических свойств и напряжений горных пород, геологических полей и обнаружения различных дефектов при селективном лазерном плавлении жаропрочного сплава для изделий аддитивного производства. Однако при эксплуатации подобных систем и комплексов на процесс регистрации акустической эмиссии неизбежно влияют сторонние факторы, вызванные добавочными (аддитивными) шумами, которые могут в значительной степени снижать точность измеряемых параметров акустического сигнала. Для повышения точности измерения параметров акустического сигнала применяют различные методы цифровой фильтрации, предназначенные для выделения диагностических параметров на фоне помех. *Цель* рассматриваемой статьи заключается в повышении точности оценки диагностически важных параметров сигнала акустической эмиссии посредством разработки метода цифровой полиномиальной фильтрации и феноменологической модели информативной составляющей для данной оценки. *Методы.* Рассмотрена реализация предложенного метода двунаправленной фильтрации модели сигнала акустической эмиссии, основанного на цифровом фильтре Баттерворта второй степени. Выделены формы информативной составляющей сигнала, измерены значения диагностических параметров акустической эмиссии, рассчитана величина относительной погрешности в процентах между моделями сигнала. Более того, на выходе метода цифровой фильтрации вычислен показатель отношения акустического сигнала к помехе для обнаружения ассоциации между этим показателем и точностью измерения диагностических параметров акустической эмиссии. Зависимость между данными показателями аппроксимирована методом наименьших квадратов и визуализирована с помощью диаграммы рассеяния, отображающей распределение данных в виде точек на координатной плоскости X и Y. *Результаты.* Выявлено, что при реализации разработанного метода повышается точность измерения диагностических параметров акустической эмиссии, где относительная погрешность измерения составляет не более трёх процентов в сравнении с вейвлет-фильтром Добеши выбранного порядка и уровня разложения.

Ключевые слова: обработка сигнала, повышение точности измерения, акустическая эмиссия, величина сигнал/помеха, акустический контроль, помехи, фильтр Баттерворта, вейвлет-фильтр

Introduction. Acoustic emission (AE) diagnostics, a critical scientific and technical challenge aimed at reducing measurement errors of AE signal parameters is the development of noise-immune methods for processing acoustic emission data. The relevance of this issue is due to the fact that noise-immune methods significantly mitigate the distorting effects of interferences caused by external factors. Such factors in AE monitoring and object operation include interferences arising from the operation of power electrical installations, inductive electrical impulses in the measurement circuit, welding processes, mechanical processing and milling of the object, loading devices, cavitation, fluid and gas flow, among others (He, 2020; Kharrat, 2015; Il et.al., 2018; Barat, 2010; Altay et.al., 2022; Altay et.al., 2025).

Among these disturbances, the suppression of impulsive electrical noise is a non-trivial task (Barat, 2010; Altay et.al., 2025). This is due to the fact that such noise comprises not only a sum of deterministic components but also variability in the amplitude values of each component. The influence of this noise reduces the accuracy of measuring informational signal components and makes it impossible to correctly interpret AE events. To mitigate distortions and reduce the impact of noise on AE signal components, various filtering methods resilient to interference are applied. However, in developing AE noise filtering methods, it is crucial to preserve the shape of the informational components that carry diagnostic information from acoustic monitoring results.

Thus, among known signal processing techniques, there is a growing relevance in seeking filtering methods that ensure minimal distortion of the AE signal's informational component at the filter output. In (Fedorov, 2022), an analysis of AE signal processing methods was performed to reduce measurement errors and improve the signal-to-noise ratio (SNR), demonstrating widespread use of wavelet filtering, empirical mode decomposition, cluster analysis, and spatiotemporal processing techniques. The analysis paid special attention to identifying the characteristics of methods that are, firstly, simple and highly accurate in mathematical implementation, and secondly, features of the processing system, such as the absence of high-order filtering schemes that affect signal shape, the selection of mathematical decomposition bases, and the need for special reference channels requiring an isolated noise signal shape for filtering.

As a result of analyzing AE data processing methods for high-precision filtering and maximum noise suppression with minimal signal shape distortion, the applicability of polynomial filtering methods was established, representing an optimal class of filters (Altay et.al., 2022). Minimal signal shape distortion is necessary for the subsequent assessment of their informative parameters in determining the technical condition of the monitored object (Altay, 2019).

The presence of distortions increases the error in assessing AE parameters and, consequently, affects the reliability of monitoring results.

The applicability of polynomial filtering methods is attributed to their capability for flexible adjustment of filtering characteristics depending on AE signal parameters, enabling the extraction of informative components from a noisy mixture of signal and interference. In synthesizing filters of this class, Butterworth polynomials are predominantly used, with Bessel, Chebyshev (Abdulkhairov, 2017), and in some cases Newton polynomials (Somefun et.al., 2022) applied less frequently. This preference arises because filters approximated by the Butterworth polynomial exhibit no ripples in pass-bands and stop-bands; their frequency response and gain are independent of polynomial order (degree), remaining uniform, monotonic, and stable compared to the mentioned filters. During signal processing, Butterworth polynomial filters generate the lowest intrinsic error values attributed to their characteristics. It is noteworthy that the roots of Butterworth (Altay et.al., 2022) and Newton polynomials (Bystrov, 2016; Bystrov et.al., 2017), with their binomial structure (Somefun et.al., 2022), are universally positioned in a circular root arrangement of the transfer function, enhancing filter system stability and making them more suitable for practical signal processing applications.

In (Stepanova, 2023), an analog topology of Butterworth filters based on operational amplifiers was proposed for the first time to improve the noise immunity of AE signal registration paths. The topology was implemented as four automatically tunable two-pole active low- and high-pass filters based on operational amplifiers (Stepanova, 2023). This filter design improved the noise immunity of the signal registration system. However, due to variations in AE signal parameters and structures, as well as interference influences, analog filtering results in insufficient noise suppression. Therefore, the focus shifts to solving tasks of digital signal processing methods for AE signals to reduce noise influence after analog filtering (Altay et.al., 2022). The presence of residual noise significantly reduces the reliability and informativeness of AE signal analysis. Thus, the application of digital filtering methods becomes a vital task.

Studies (Altay et.al., 2022; Barat, 2010; Fedorov, 2022) have shown that the implementation of digital filters approximated by Butterworth polynomials for noise suppression in AE signal processing remains insufficiently explored. A comparative analysis and efficiency evaluation of digital filtering methods specifically Butterworth and Bessel polynomial high-pass and low-pass filters were conducted to reduce measurement errors of AE parameters and improve SNR. It was established that combining spectral analysis methods with flexible filter parameter adjustments maximizes the SNR (Altay et.al., 2022) and reduces measurement errors of amplitude and temporal signal parameters (Altay et.al., 2022). Works (Altay et.al., 2019; Altay et.al., 2022) demonstrated that among polynomial filtering methods, filters approximated by Butterworth polynomials ensure high signal processing accuracy with minimal distortion of the informative components of AE signals. Among Butterworth filters, high-pass polynomial filters achieved the highest SNR values and the lowest AE parameter measurement errors. This finding substantiates the selection of this method for assessing the relationship between signal informational components and noise during multichannel AE data acquisition (Altay et.al., 2022, Fedorov, 2022).

Unlike (Altay et.al., 2022, Altay et.al., 2025), this study examines the predictive assessment of the impact of SNR on the measurement error of AE diagnostic parameters produced at the output of Butterworth polynomial digital filtering methods, compared to the well-established Daubechies wavelet filters (Kharrat et.al, 2017). For polynomial digital filtering methods, the concept of a filter "producing" a signal is applied, as introduced in the monograph by B.R. Levin (Zakharov, 2022) when determining the capabilities of filters for AE signal processing. It is important to note that in (Zakharov, 2022), the term "producing" was used in the context of matched filtering of signals. Instead of the conventional "signal-to-noise ratio," the term "signal-to-interference ratio" is used here, as the study considers the impact of interference on the measurement error of AE parameters.

The objective of this research is to develop a predictive regression model describing the dependence of the signal-to-interference ratio on the measurement error of AE parameters at the output of polynomial filtering methods. The predictive model, characterizing the impact of SNR on the measurement error of AE parameters, is developed based on a machine learning approach—linear regression. The choice of this method for model development is justified by its operational efficiency, high sensitivity to the analyzed data (Elforjani, 2018; Ponkratov, 2023; Begentayev, 2025; Begentayev, 2024), and the absence of requirements for special training of AE data samples obtained from the monitored object.

Material and Research Methodology

Research Material. The initial material for developing the predictive model comprised the measured values of the signal-to-noise ratio (SNR) and relative error obtained during the implementation of an additive mixture of (1) a generated acoustic emission (AE) signal (Fedorov, 2022) and (2) noise (Altay et.al., 2022) at the output of digital filtering methods. This approach to noise modeling allows simulating a provocative noise background for the development of a predictive model aimed at estimating diagnostic AE parameters at the output of filtering methods.

Research Methodology. The synthesis of infinite impulse response (IIR) digital filters, specifically the Butterworth high-pass filter, was performed in a normalized frequency range using analog prototypes through bilinear transformation (Altay et.al., 2022). To avoid the distorting effects introduced by high-order filters on AE signal parameters and to reduce computational complexity in calculating filter transfer functions, second-order polynomials (n = 2) were selected (Altay et.al., 2022). For the considered IIR filters, the cutoff frequency of the generated informational component of the AE signal was set at 240 kHz, with a sampling frequency of 4 MHz (Altay et.al., 2019; Altay et.al., 2022). Based on these frequencies, the transfer function of the second-order Butterworth digital filter was calculated. The derived transfer functions of continuous high-pass filters and their bilinear transformations are presented in Table 1.

Table 1. Transfer Functions of the Designed High-Pass Filters

Filter Polynomial, $A(s)$	Transfer functions	
	Continuous, $W(s)$	Discrete, $W(z)$
Butterworth $s^2 + 1{,}414\Omega_C s + \Omega_C^2$	$\frac{s^2}{s^2 + 0{,}176s + 0{,}015}$	$\frac{0{,}915z^2 - 1{,}831z + 0{,}915}{z^2 - 1{,}824z + 0{,}832}$

Note. s – complex variable of the continuous-time transfer function; Ω_C – cutoff frequency of the filter; z – complex variable of the discrete-time transfer function.

To minimize distortions of the informational component of the processed signal, bidirectional filtering was applied. Unlike conventional unidirectional filtering (input-output), bidirectional filtering involves processing the signal "in both directions." In this approach, AE signals are filtered first in the forward and then in the reverse directions (Altay et.al., 2022), with distortions introduced by the filtering system mutually compensated. The structural scheme of the bidirectional implementation of high-pass filters, as well as their convolution in the frequency domain for AE signal processing, is detailed in (Altay et.al., 2022).

Following the recommendations of [18], the relative measurement error (δ) was assessed for the following AE diagnostic parameters: root mean square deviation (δ_U), root mean square value (RMS), signal amplitude (U), and the MARSE (Measured Area of the Rectified Signal Envelope) energy parameter. The selection of these AE parameters is justified by their sensitivity in identifying relationships with the properties of the AE source during technical condition monitoring of the tool (Elforjani, 2018).

The statistical parameters characterize: the deviation of the amplitude samples of the analyzed signal from the mean value (σU), the power or root mean square value of the signal (RMS), and the maximum amplitude of the electrical signal voltage (U). The MARSE parameter characterizes the contribution of the voltage oscillation amplitude to the total energy of the AE signal, calculated under the area or squared envelope of the pulse. The AE signal envelope is a special line that connects the peak amplitudes of the positive half-wave of the analyzed signal (Elforjani, 2018). The calculation of the aforementioned amplitude parameters was carried out using built-in functions of the MATLAB software environment. When calculating the relative error of these parameters, the initial (reference) signal form was taken as the experimentally generated test AE signal described in (Altay et.al., 2022).

The predictive model characterizing the influence of the SNR on the relative error in estimating AE parameters was developed using linear regression (Altay, 2019). The relationship between measurement error and SNR was approximated using the least squares method and visualized through a scatter plot illustrating the distribution of the two variables: SNR and the relative measurement error of AE parameters.

The relationship between SNR and relative error was assessed using Pearson's correlation coefficient (r). The strength of the correlation was evaluated according to Chaddock's scale: r = 0.4 – 0.7 indicates a moderate correlation, r = 0.7–0.9 a strong correlation and r = 0.9 –0.99 a very strong correlation (Begentayev, 2025). The adequacy of the constructed regression model was assessed using the coefficient of determination (R^2). The correlation was considered significant and non-random at a significance level of $p < 0.05$

Research results

An assessment of the influence of the signal-to-noise ratio (SNR) on the measurement error of acoustic emission (AE) parameters after filtering noisy signals was performed for SNR values of –10 dB, –5 dB, 0 dB, 5 dB, and 10 dB (Altay et.al., 2022). Figure 1 presents scatter plots illustrating the relationship between the SNR values before and after processing AE signals using a Butterworth filter.

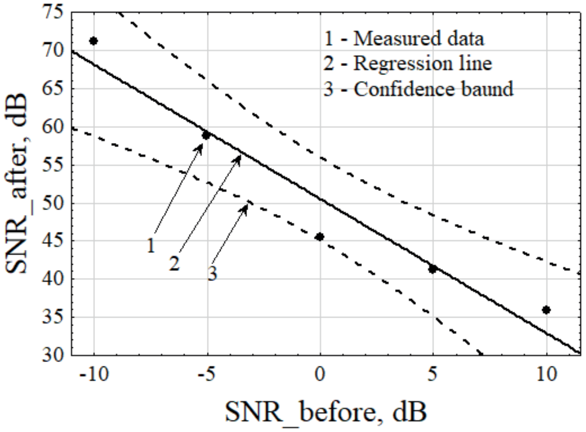
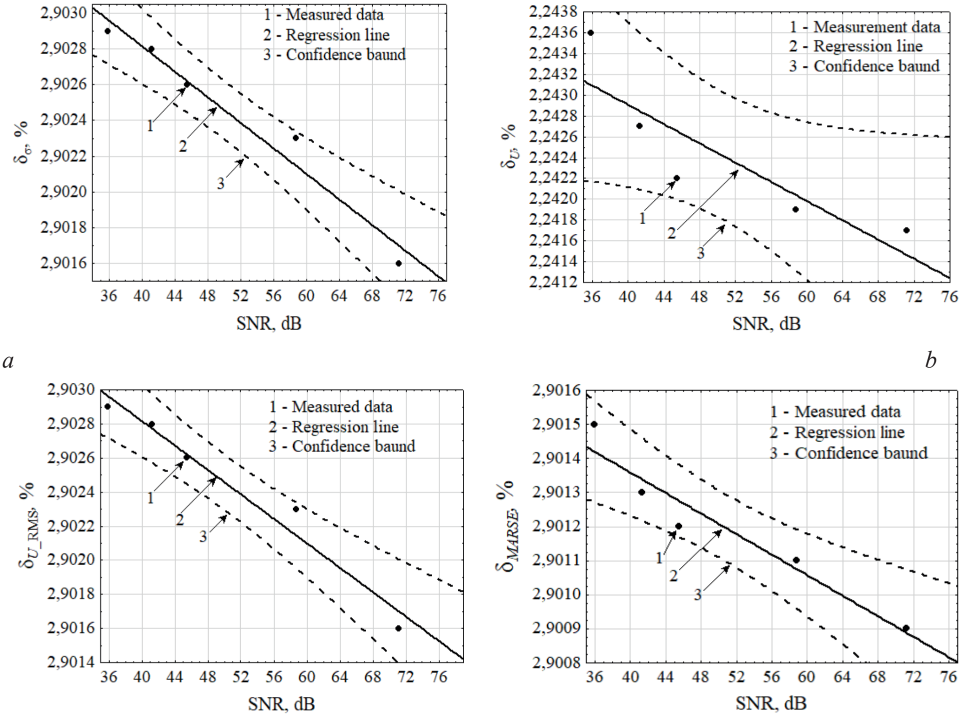


Figure 1. Signal-to-noise ratio dependence before and after processing

From the dependencies shown in Figure 1, it follows that as the SNR of the noisy signal decreases by –1 dB, the SNR values after processing increase accordingly. The evaluation of the pairwise correlation revealed a statistically significant strong inverse correlation between the SNR measurements before and after filtering, specifically $r = –0.972$, $R^2 = 0.946$, with $p = 0.005$. This finding indicates a reduction in the noise component's influence on the AE signal due to the enhancement of the SNR at the filter output. Consequently, specific SNR values were selected for further assessment, establishing functional dependencies and developing a statistical model to examine the impact of SNR on the measurement error of AE parameters. The scatter plots of the regression dependencies are presented in Figure 2.



a *b*

c *d*

Figure 2. Error of measurement of the acoustic emission parameters in dependence value signal-to-noise ratio for Butterworth filters (Altay, 2022): σ*U* (*a*); *U* (*b*); *U*RMS (*c*); MARSE (*d*)

Statistical modeling results demonstrate that as the SNR values increase, the measurement error of AE parameters at the filter output decreases (Altay, 2022). The measurement error does not exceed 3%. Furthermore, an inverse correlation is observed between SNR values and the relative measurement error, indicating a decline in AE parameter measurement errors with increasing SNR.

The statistical model describing this relationship is expressed through a linear regression equation, with its functionality evaluated by the coefficient of determination (R^2) and the strength of correlation (r) based on the model's significance level (p-value). For the filtering method (Altay et.al., 2022) based on the Butterworth filter, the following regression equations were obtained:

$y_{\delta\_\sigma} = -3{,}584 \cdot 10^{-5} \cdot \text{SNR} + 2{,}904,\ R^2 = 0{,}964,\ p = 0{,}002;$

$y_{\delta\_U} = -4{,}625 \cdot 10^{-5} \cdot \text{SNR} + 2{,}244$ at $r = -0{,}871,\ R^2 = 0{,}759,\ p = 0{,}050;$

$y_{\delta\_\text{RMS}} = -3{,}584 \cdot 10^{-5} \cdot \text{SNR} + 2{,}904$ at $r = -0{,}981,\ R^2 = 0{,}964,\ p = 0{,}002;$

$y_{\delta\_\text{MARSE}} = -1{,}5 \cdot 10^{-5} \cdot \text{SNR} + 2{,}902$ at $r = -0{,}963,\ R^2 = 0{,}928,\ p = 0{,}008,$

where SNR denotes the signal-to-noise ratio value.

The results of the regression analysis confirmed the influence of the SNR on the measurement error of AE parameters. This influence is supported by a statistically significant strong inverse correlation between the SNR and the relative measurement error. The minimum (R^2 = 0.759) and maximum (R^2 = 0.964) determination coefficients (for method (Altay, 2022)) are close to one, which reflects the accuracy of the developed statistical model. A statistical model is considered accurate when the coefficient of determination approaches. In this study, significance levels of $p = 0.05$ at $p < 0.05$ indicate the non-randomness of the observed correlations. It should also be noted that AE parameters measured at high SNR values may be essential for predictive analytics of the technical condition of the monitored object (Elforjani, 2018).

Discussion

The amplitude parameters of acoustic emission (AE) signals exhibit the strongest correlation with the characteristics of the AE source imparted by the inspected object and effectively describe the energy content of acoustic phenomena (Barat, 2010). However, the accuracy and reliability of amplitude parameter estimation are significantly affected by noise, which reduces the signal-to-noise ratio and increases the estimation error of AE parameters.

The data presented in this study demonstrate a statistically significant impact of SNR on the relative error in estimating AE parameters. The relative measurement error of AE parameters did not exceed 3% at an SNR level of 71 dB. This result was obtained using a filter approximated by a Butterworth polynomial (Altay, 2022). To validate the influence of SNR on the relative error, the obtained results were compared with existing AE noise filtering methods. For comparison, a wavelet filter was selected (Kharrat, 2017), with its statistical dependencies illustrated in Figure 3.

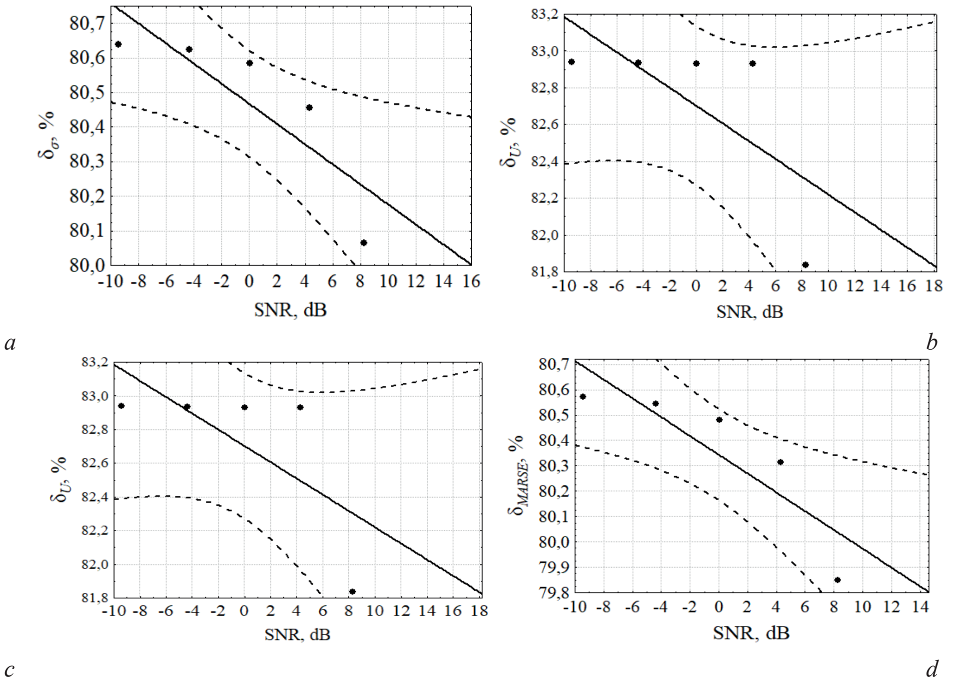


Figure 3. Error of measurement of the acoustic emission parameters in dependence value signal-to-noise ratio for wavelet filters (Kharrat, 2017): σ_U (a); δ_U (*b*); δ_{RMS} (c); δ_{MARSE} (*d*)

From the dependencies presented in Figure 1, it is evident that, similar to the Butterworth filter, an increase in SNR leads to a decrease in the relative error. However, when comparing the relative error values, the wavelet filter method exhibited a relative error of 83% at an SNR of 8 dB. In (Ovcharuk et. all., 2017), it was shown that the relative error in determining AE signal parameters can be unstable, ranging from 29.22% to 82.72%.

The assessment results obtained in this study indicate that the relative error values for the wavelet filter fall within the discussed error range, as reported in (Ovcharuk et.all., 2017), whereas for the developed method (Altay et. all., 2022), the error did not exceed 3%. The high relative error associated with the wavelet filter is due to its tendency to not only attenuate noise but also to smooth and distort the amplitude components of the experimental-test signal waveform during processing, as also observed in (Altay et. all., 2022). In addition to smoothing the informative components of the AE signal, the wavelet filter blurs the signal shape, which was identified in studies (Ovcharuk et. all., 2017).

It is worth noting that the enhanced performance of processing complex structured signals using Butterworth filters was previously reported in (Rakshit et.all., 2018), while wavelet filters were examined in (Altay et. all., , 2025). For various input data sets, an improvement in signal processing performance using the Butterworth filter was also observed in (Malghan et. all., 2020).

An inverse relationship exists between SNR values and relative errors for the wavelet filter (Kharrat et. all.,2017). The correlation metrics for the wavelet filter-based method are as follows:

$y_{\delta\sigma} = –0{,}029 \cdot \text{SNR} + 80{,}467$ at $r = –0{,}847$, $R^2 = 0{,}718$, $p = 0{,}069$;
$y_{\delta U} = –0{,}048 \cdot \text{SNR} + 82{,}702$ at $r = –0{,}687$, $R^2 = 0{,}473$, $p = 0{,}199$;
$y_{\delta \text{СКЗ}} = –0{,}029 \cdot \text{SNR} + 80{,}465$ at $r = –0{,}848$, $R^2 = 0{,}719$, $p = 0{,}069$;
$y_{\delta MARSE} = –0{,}037 \cdot \text{SNR} + 80{,}343$ at $r = –0{,}867$, $R^2 = 0{,}753$, $p = 0{,}056$.

In statistical measurement processing theory, a correlation coefficient (r) value greater than 0.700 indicates a strong relationship. In this study, the correlation coefficients for each established dependency were in the following ranges: for the processing method (Altay et. all., 2022), $r = –0.871$ to $r = –0.981$ with $p < 0.05$; for the filtering method (Kharrat et. all., 2017), r = –0.687 to r = –0.867 with $p > 0.05$. The strong statistically significant correlation between SNR and relative error for method (Altay et. all., 2022) is attributed to the enhanced processing performance in terms of accuracy and noise immunity of AE signals (Altay, 2022). Due to the limited performance of the wavelet filter (Kharrat et. all., 2017) in terms of accuracy and noise immunity, the correlation coefficient characterizing the strength of the dependency is significantly lower compared to the Butterworth filter-based method (Altay et. all., 2022).

The coefficient of determination (R^2) of the regression model for the proposed method (Altay et. all., 2022) exceeded $R^2 > 0.759$, indicating a high convergence of measurement data with the regression line, in contrast to the wavelet filter $R^2 > 0.473$ (Kharrat et. all., 2017), obtained using a linear model.

The conducted study demonstrated that reducing the measurement error of AE parameters can be effectively achieved using a processing method based on the Butterworth filter, owing to its high noise immunity (Altay et. all., 2022). The novelty of this research lies in the development of a predictive model that describes the influence of SNR on measurement error to enhance the accuracy of AE parameter estimation through filter application. Previous studies have not adequately addressed this aspect.

Conclusion

This study presents the development of a predictive model for assessing the impact of SNR on the measurement error of AE diagnostic parameters during digital signal processing using Butterworth and Daubechies wavelet filters. A strong and statistically significant inverse correlation between SNR and the relative error in parameter measurement was established. It was found that at high SNR levels, the Butterworth filter can ensure a relative measurement error of AE diagnostic parameters not exceeding 3% at an SNR of 71 dB.

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