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THE JOURNAL WAS FOUNDED IN 1940

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The scientific journal News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences has been indexed in the international abstract and citation database Scopus since 2016 and demonstrates stable bibliometric performance.

The journal is also included in the Emerging Sources Citation Index (ESCI) of the Web of Science platform (Clarivate Analytics, since 2018).

Indexing in ESCI confirms the journal's compliance with international standards of scientific peer review and editorial ethics and is considered by Clarivate Analytics as part of the evaluation process for potential inclusion in the Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), and Arts & Humanities Citation Index (AHCI).

Indexing in Scopus and Web of Science ensures high international visibility of publications, promotes citation growth, and reflects the editorial board's commitment to publishing relevant, original, and scientifically significant research in the fields of geology and technical sciences.

«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық рефеативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық рефеативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылымды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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PREDICTIVE CONTROL OF DIAGNOSTICALLY SIGNIFICANT PARAMETERS OF ACOUSTIC EMISSION USING MACHINE LEARNING: NEW DATA

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Abstract. *Relevance.* Modern non-destructive testing systems based on acoustic testing, namely acoustic emission phenomena, are one of the sensitive elements for identifying the acoustic properties and stresses of various rocks and geological fields, and allow for the detection of various defects. One of the main factors hindering the application of the acoustic emission method is the influence of noise and interference of varying intensity and nature, which mainly occur during signal recording. The presence of interference and noise significantly reduces the information value of the method and the accuracy of the estimated diagnostic parameters during testing. Improving the information value of the method and its accuracy depends on the effectiveness of the digital processing method based on interference and noise filtering. The goal of this article is to develop a digital filtering method for acoustic emission signals to improve the processing efficiency and the accuracy of assessing diagnostically significant components during testing. *Method.* The article presents the results of the implementation of a sequential high-frequency digital filtering method based on the root characteristics of the Butterworth polynomial of even degree. From all the recorded acoustic emission signals, only fragments of the informative components were extracted. Furthermore, the processing effectiveness was assessed by calculating the signal-to-noise ratio, diagnostic amplitude parameters (MARSE), and power. Predictive models of the emission diagnostic parameters were developed using a machine learning method – linear regression the reliability of which is represented by the correlation coefficient, determination coefficient, and significance of the model. The relationship between these parameters was approximated using the least-squares method and visualized using a scatterplot and a Tukey diagram, which displays the data distribution as points on an x- and y-coordinate plane. *Results.* It was found that the sequential high-pass digital polynomial filtering method yields a signal-to-noise ratio of more than 1.5 dB on average. Understanding the discovered relationship, which can be used in developing predictive models, will significantly expand the capabilities of acoustic monitoring for assessing the properties and stresses of various rocks and geological fields, and for identifying defects. Results obtained with a statistically significant and non-random relationship can confirm the viability and functionality of the developed predictive model.

Keywords: Digital filter, Butterworth polynomial, acoustic emission, sequential processing, machine learning, predictive control

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МАШИНАЛЫҚ ОҚЫТУ ӘДІСІН ҚОЛДАНА ОТЫРЫП, АКУСТИКАЛЫҚ ЭМИССИЯНЫҢ ДИАГНОСТИКАЛЫҚ МАҢЫЗДЫ ПАРАМЕТРЛЕРІН БОЛЖАМДЫ БАҚЫЛАУ: ЖАҢА ДЕРЕКТЕР

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Аннотация. *Өзектілігі.* Акустикалық сынаққа негізделген қазіргі заманғы бұзбайтын сынақ жүйелері, атап айтқанда акустикалық эмиссия құбылыстары, әртүрлі тау жыныстары мен геологиялық өрістердің акустикалық қасиеттері мен кернеулерін анықтауға арналған сезімтал элементтердің бірі болып табылады және әртүрлі ақауларды анықтауға мүмкіндік береді. Акустикалық эмиссия әдісін қолдануға кедергі келтіретін негізгі факторлардың бірі - негізінен сигналды жазу кезінде пайда болатын әртүрлі қарқындылық пен сипаттағы шу мен кедергілердің әсері. Кедергі мен шудың болуы әдістің ақпараттық құндылығын және сынақ кезіндегі бағаланған диагностикалық параметрлердің дәлдігін айтарлықтай төмендетеді. Әдістің ақпараттық құндылығын және оның дәлдігін жақсарту кедергі мен шуды сүзуге негізделген сандық өңдеу әдісінің тиімділігіне байланысты. Бұл мақаланың мақсаты – сынақ кезінде өңдеу тиімділігін және диагностикалық маңызды компоненттерді бағалау дәлдігін арттыру үшін акустикалық эмиссия сигналдары үшін сандық сүзу әдісін әзірлеу. *Әдіс.* Мақалада жұп дәрежелі Баттерворт полиномының түбірлік сипаттамаларына негізделген тізбекті жоғары жиілікті сандық сүзу әдісін енгізу нәтижелері ұсынылған. Барлық жазылған акустикалық эмиссия сигналдарынан тек ақпараттық компоненттердің фрагменттері алынды. Сонымен қатар, өңдеу тиімділігі сигнал-шуыл қатынасын, диагностикалық амплитуда параметрлерін (MARSE) және қуатты есептеу арқылы бағаланды. Сәулелену диагностикалық параметрлерінің болжамдық модельдері машиналық оқыту әдісін – сызықтық регрессияны қолдана отырып жасалды, оның сенімділігі корреляция коэффициентімен, анықтау коэффициентімен және модельдің маңыздылығымен көрсетіледі. Бұл параметрлер арасындағы байланыс ең кіші квадраттар әдісін қолдана отырып жуықтап есептелді және шашыраңқы графигін және деректердің таралуын x және y координаталық жазықтығындағы нүктелер ретінде көрсететін Туки диаграммасын қолдана отырып көрнекіленді. *Нәтижелер*. Тізбекті жоғары жиілікті сандық полиномдық сүзгілеу әдісі орташа есеппен 1,5 дБ-ден астам сигнал-шуыл қатынасын беретіні анықталды. Болжамдық модельдерді әзірлеуде пайдаланылуы мүмкін анықталған байланысты түсіну әртүрлі тау жыныстары мен геологиялық кен орындарының қасиеттері мен кернеулерін бағалау және ақауларды анықтау үшін акустикалық мониторинг мүмкіндіктерін айтарлықтай кеңейтеді. Статистикалық тұрғыдан маңызды және кездейсоқ емес байланыспен алынған нәтижелер әзірленген болжамдық модельдің өміршеңдігі мен функционалдығын растай алады.

Түйін сөздер: сандық сүзгі, Баттерворт полиномы, акустикалық эмиссия, тізбекті өңдеу, машиналық оқыту, болжамды басқару

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ПРОГНОЗИРУЮЩИЙ КОНТРОЛЬ ДИАГНОСТИЧЕСКИ ЗНАЧИМЫХ ПАРАМЕТРОВ АКУСТИЧЕСКОЙ ЭМИССИИ МЕТОДОМ МАШИННОГО ОБУЧЕНИЯ: НОВЫЕ ДАННЫЕ

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Аннотация. *Актуальность.* Современные системы неразрушающего контроля, основанные на методе акустической эмиссии, являются высокочувствительным инструментом для идентификации акустических свойств и напряжённого состояния горных пород и геологических сред, а также для обнаружения различных дефектов. Вместе с тем одним из основных факторов, сдерживающих широкое применение метода акустической эмиссии, является влияние шумов и помех различной природы и интенсивности, возникающих при регистрации сигналов. Наличие помех существенно снижает информативную ценность метода и точность оценки диагностических параметров. Повышение точности и информативности напрямую зависит от эффективности методов цифровой обработки сигналов, основанных на фильтрации шумов. *Цель* Разработать метод цифровой фильтрации сигналов акустической эмиссии для повышения результативности обработки и точности оценки диагностически значимых параметров при контроле. *Метод*. авлены результаты реализации метода последовательной высокочастотной цифровой фильтрации, основанного на корневых характеристиках полинома Баттерворта чётной степени. Из зарегистрированных сигналов акустической эмиссии выделялись информативные фрагменты. Оценка эффективности обработки выполнялась с использованием показателей отношения сигнал/шум, а также диагностических амплитудных параметров (MARSE, мощность и др.). Для прогнозирования диагностических параметров применялись методы машинного обучения, в частности линейная регрессия. Достоверность моделей оценивалась с использованием коэффициентов корреляции, детерминации и статистической значимости. Зависимости между параметрами аппроксимировались методом наименьших квадратов и визуализировались с помощью диаграмм рассеяния и диаграмм Тьюки, отражающих распределение данных. *Результаты*. Установлено, что предложенный метод последовательной высокочастотной цифровой фильтрации обеспечивает увеличение отношения сигнал/шум в среднем более чем на 1,5 дБ. Выявленные закономерности, использованные при построении прогнозных моделей, позволяют существенно расширить возможности акустического контроля при оценке свойств и напряжённого состояния пород и геологических сред, а также при выявлении дефектов. Полученные результаты, характеризующиеся статистически значимой зависимостью, подтверждают работоспособность и практическую применимость разработанной предиктивной модели.

Ключевые слова: Цифровой фильтр, полином Баттерворта, акустическая эмиссия, последовательная обработка, машинное обучение, предиктивный контроль

Introduction. Statistical evaluation of acoustic emission (AE) signal parameters is currently one of the most important stages in the analysis of measurement data after applying primary signal processing methods, namely, its filtration (Kharrat, 2016; Barat, 2010; He, 2021; Altay et.al, 2022).

This is due to the fact that the noise component of the AE signal reduces the accuracy of the assessment of the primary and secondary diagnostic indicators characterizing the set of features by which it is possible to determine the state of the tested object (TO). Improving the accuracy of the indicator assessment and, consequently, the reliability of the AE diagnostics of the TO mainly depends on the efficiency of the applied primary signal processing methods (Altay et.al, 2022). The presence of the noise component of the signal and its insufficient attenuation significantly reduces the accuracy of the assessment of AE indicators (Kharrat, 2016; Barat, 2010; He, 2021; Altay et.al, 2022), therefore the use of filtration methods is an important link in the secondary signal processing when assessing the diagnostic indicators of AE.

In this article, in contrast to previously published works (Kharrat, 2016; Barat, 2010; He, 2021; Altay et.al, 2022), during the experimental testing of the developed digital filter, which generates an estimate based on the criteria of maximum signal-to-noise ratio and minimum standard deviation of the signal, the results of the primary processing of noisy natural signals and the statistical evaluation of specific AE parameters are presented.

The aim of the research is to improve the efficiency of AE signal processing by implementing digital polynomial filtering to evaluate the statistical distinguishability of noisy and filtered signals, and to calculate secondary diagnostic indicators of AE and their significance.

Materials and methods. The study utilized signals recorded during the milling process of an aluminum alloy plate using two carbide tool cutters. One of the cutters was defect-free, while the other had a defect in the form of a chipped thread at the end of the working part of the tool. During the experiment, the results of 48 signals (24 for the defect-free cutter and 24 for the cutter with a defect) were recorded and digitized using a certified AE measuring system (SCAD). All signals contained at least 4000 measurements (q) at a sampling frequency of 4 MHz and were recorded under uniform conditions in the absence of external environmental factors affecting the experimental results. The obtained registration results were processed using the developed AE signal processing system based on a bidirectional filtering scheme to isolate the signal components of both information (*s*) and noise (*n*) (Gomez, 2012; Zakharov, 2022; Elforjani, 2018).

Statistical analysis of the recording and processing results. In this section of the article, a double descriptive analysis was used to describe the measurement results and their processing, according to the recommendation (Altay et.al 2025). Double descriptive analysis allows us to characterize the entire measurement set and select a statistical method for assessing the distinguishability of readings between noisy and filtered signals when the measurement data deviate from the Gaussian distribution law. Noisy and filtered signal readings are presented as the arithmetic mean (*u*), standard deviations (σ), median (Me), and quartiles (*Q*1–*Q*3). The distribution of signal readings was assessed based on the calculation of the Lilliefors criterion, used for measurements greater than $q > 50$.

Results and discussion. During the experimental studies, the recording results were processed in two stages. In the first stage, a discrete Fourier transform was used to empirically estimate the frequency of the recorded signals to determine the cutoff frequency of the adjustable filter. In the second stage, the MATLAB SOFTWARE PACKAGE was used for initial signal processing and to calculate the AE parameters for further statistical analysis. Figure 1 shows the results of the spectral analysis of the noisy AE signal during the inspection of a flawless and a flawed tool.

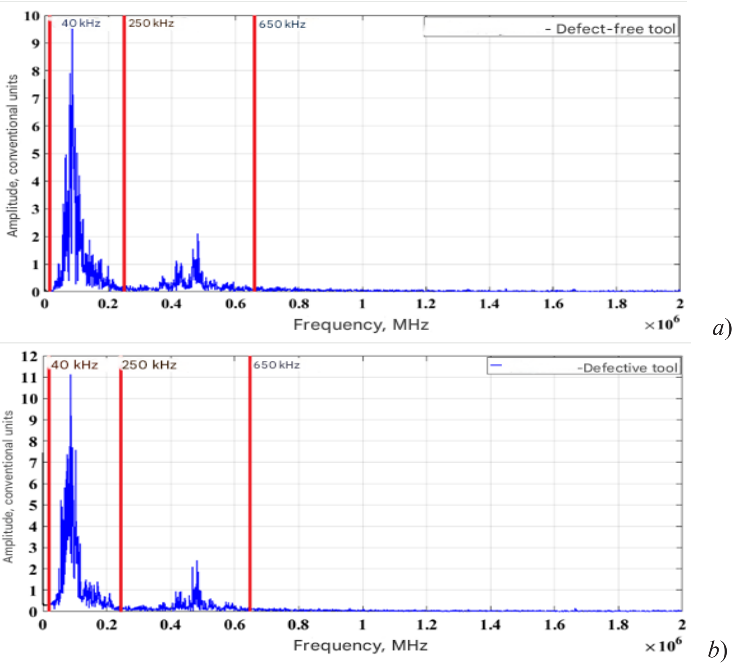


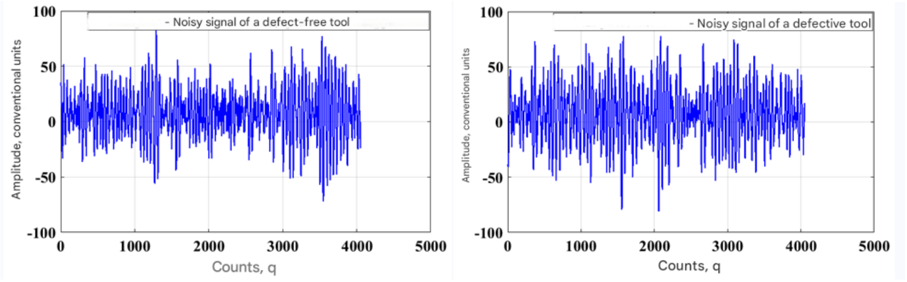
Figure 1. Frequency spectrum of AE signals during testing:
a) a defect-free tool; *b*) a defective tool.

Based on the results of the spectral analysis, it was noted that the signal amplitude during testing of a defective instrument exceeds the signal amplitude during testing of a defect-free instrument by approximately 1.5 units, and the amplitude of the interference component of the signal, located above the spectrum of the information signal, has insignificant variability depending on the frequency.

The results of the first stage of data processing showed that the frequencies of natural noisy signals for a defect-free and defective tool were identified in the frequency range from 40 kHz to 650 kHz. Among this frequency, the range of the information component is located in the interval from 40 kHz to 250 kHz, and the interference component is from 250 kHz to 650 kHz. The obtained results of this assessment coincide with the available experimental data, where it is noted that the frequency content of the AE signals obtained during the milling process can be in the frequency range from 40 kHz to 350 kHz (Gomez, 2012). This provides a justification for choosing the upper frequency range of the AE signal, namely 250 kHz for adjusting the high-pass filter (HPF) (Gomez, 2012) in order to weaken the influence of the interference identified above the range of the information component of the signal.

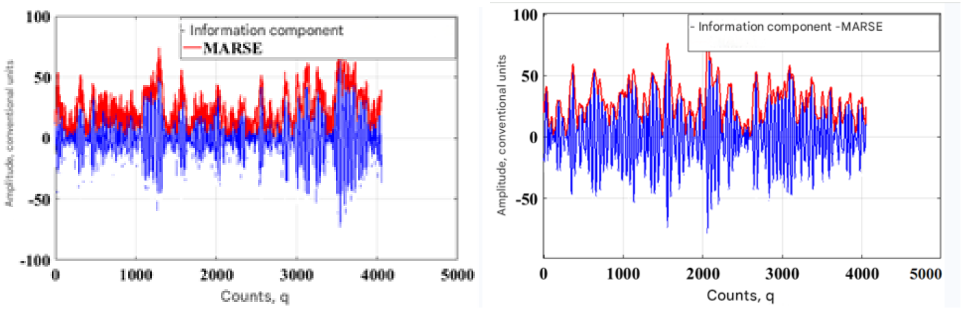
To process the AE signal recording results, the digital filter characteristics were analyzed using the amplitude-frequency response (AFR) and zero-pole diagram (NPD) (Gomez, 2012). The filters AFR showed that the high-pass filter at a cutoff frequency of 250 kHz is ripple-free, monotonic, and stable, both in the signal passband and in the interference suppression band. The roots of the filter's transfer function structure are located within a unit-radius circle on the NPD and are stable. All analyzed characteristics of the designed filter provide a significant advantage for isolating not only the information component but also the interference component.

The results of the second stage of data processing showed that a filtering method based on a sequential high-pass filter, set to a cutoff frequency of 250 kHz, allows for the extraction of both the information and interference components of the AE signals. For better visualization and comparison of the recording results, Figures 2–4 present the extracted signals of the information and interference components of the defective and defective instruments as a single sample.



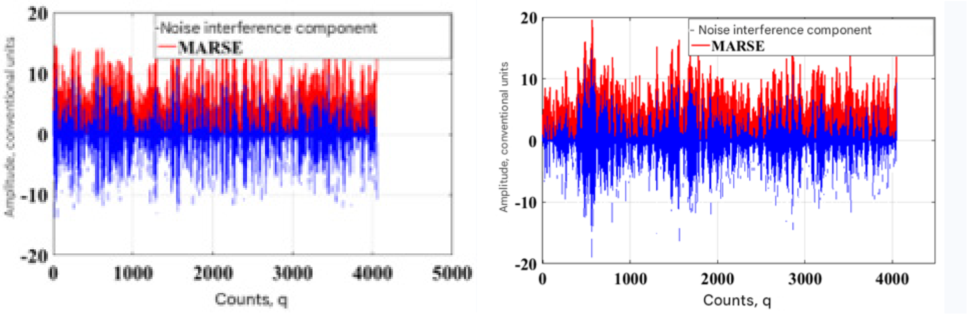
a) *b*)

Figure 2. Comparison of initial signals during AE testing:
a) defect-free tool; *b*) defective tool.



a) *b*)

Figure 3. Comparison of information components during AE control:
a) a defective tool; *b*) a defective tool.



a) *b*)

Figure 4. Comparison of interference components during AE control:
a) a defective tool; *b*) a defective tool.

A comparative analysis of the waveforms presented in Figures 2–4 revealed differences in the AE waveforms obtained during inspection of defective and defect-free tools. The information component during AE inspection of a defect-free tool (Figure 3a) differs significantly from the information component during inspection of a defective tool (Figure 3b), while the waveform is similar to the AE phenomenon when compared with a noisy signal (Figure 2), where the information component is masked by the interference component (Figure 4). The distinguishability of the noisy and filtered signals obtained during inspection of defective and defect-free tools was analyzed using statistical analysis.

Descriptive analysis revealed differences in the u and Me values in the raw and filtered signal readings for both the flawless and defective instruments. The median quartile values $Q1$ - $Q3$ characterize significant scatter in the noisy set of measurements compared to the same set in the filtered signals. The presence of this scatter in the $Q1$-$Q3$ quartiles $x_i(q)$ and $s_i(q)$ relative to their median should be characterized by the influence of the noise component. The difference in the values of the u and Me indicators indicates that the data deviate from the Gaussian distribution law, since $u \neq$ Me, as evidenced by the p - value of the Lilliefors criterion (see Tables 1 and 2).

Table 1. Statistical characteristics of the analyzed AE signals for a defect-free tool.

No.	Indicators of noisy AE signals, $x_i(q)$			Indicators of the information component of AE signals, $s_i(q)$		
	$u \pm \sigma$, mV. ($q > 4000$)	Me [$Q1$; $Q3$], mV ($q > 4000$)	p -value *	$u \pm \sigma$, mV ($q > 4000$)	Me [$Q1$; $Q3$], mV ($q > 4000$)	p - value **
1	7,68±22,19	8,000 [-6,000 ; 22,000]	0.01	0.132±19.746	0.225 [-12.359 ; 12.298]	0.01
2	0.38±30.38	0,000 [-13,000 ; 14,000]		0.019±24.248	0.319 [-10.137 ; 10.869]	
3	6,61±27,19	6,000 [-5,000 ; 18,000]		0.142±20.787	0.086 [-8.329 ; 8.583]	
4	2,78±24,01	2,000 [-8,000 ; 15,000]		0.115±17.429	0.216 [-7.824 ; 8.170]	
5	7,70±19,36	7,000 [-5,000 ; 21,000]		0.171±16.967	0.190 [-11.380 ; 11.607]	
6	0.37±83.41	0,000 [-29,000 ; 31,000]		0.050±63.290	0.150 [-22.233 ; 23.306]	0.006
7	6,63±61,91	6,000 [-22,000 ; 34,000]		0.088±44.326	0.287 [-21.730 ; 21.563]	0.01
8	2,75±66,16	4,000 [-27,000 ; 31,000]		0.039±45.297	1,092 [-21,281 ; 19,982]	
9	7,10±45,92	3,000 [-65,000 ; 71,000]		0.282±41.616	0.838 [-28.184 ; 27.916]	0.003
10	0.24±170.9	2,000 [-68,000 ; 71,000]		0.019±121.385	0.236 [-50.087 ; 50.220]	0.01
11	6,58±141,8	7,000 [-44,000 ; 57,000]		0.029±87.488	0.018 [-33.948 ; 34.541]	
12	2,64±166,8	3,000 [-65,000 ; 71,000]		0.084±105.629	0.369 [-45.225 ; 44.769]	
13	7.00±61.19	7,000 [-32,000 ; 45,000]		0.612±56.145	0.420 [-36.050 ; 34.376]	
14	0.09±303.4	3,000 [-67,000 ; 66,000]		0.248±194.055	1,827 [-49,695 ; 47,714]	
15	6.50±246.5	4,000 [-48,000 ; 63,000]		0.027±160.821	3,109 [-40,571 ; 43,224]	
16	2,79±253,4	3,000 [-63,000 ; 68,000]		0.655±174.735	1,019 [-44,728 ; 46,950]	
17	7,45±101,0	6,000 [-62,000 ; 77,000]	0.05	0.273±91.886	0.681 [-64.492 ; 64.131]	0.008
18	0.23±196.1	2,000 [-79,000 ; 77,000]	0.01	0.628±141.708	0.184 [-58.479 ; 57.888]	0.01
19	6,78±126,6	6,000 [-49,000 ; 61,000]		0.091±92.403	0.515 [-41.952 ; 42.607]	
20	2,78±174,0	3,000 [-58,000 ; 61,000]		0.158±114.559	0.297 [-40.512 ; 41.193]	
21	6,82±88,82	8,000 [-53,000 ; 66,000]		0.388±81.595	1,126 [-54,714 ; 54,642]	0.007
22	0.35±164.7	0,000 [-67,000 ; 69,000]		0.174±126.609	1,152 [-51,558 ; 52,033]	0.01
23	6,70±131,6	6,000 [-50,000 ; 63,000]		0.176±91.701	1,174 [-41,878 ; 40,518]	
24	2.66±123.3	2,000 [-47,000 ; 51,000]		0.514±86.873	0.938 [-35.783 ; 34.382]	
p - value ***	$p < 0.05$					

Note.
p - value * - the value of the Lilliefors criterion for noisy data,
p - value ** - the value of the Lilliefors criterion for the information component data,
p - value *** - value of the Wilcoxon test for data between before and after treatment.

Table 2. Statistical characteristics of the analyzed AE signals for a defective tool.

No.	Indicators of noisy AE signals, $x_i(q)$			Indicators of the information component of AE signals, $s_i(q)$		
	$u \pm \sigma$, mV ($q > 4000$)	Me [$Q1$; $Q3$], mV ($q > 4000$)	p - value *	$u \pm \sigma$, mV ($q > 4000$)	Me [$Q1$; $Q3$], mV ($q > 4000$)	p - value **
1	7,453±25,903	7,000 [-10,000 ; 25,000]	0.05	0.182±23.142	0.092 [-15.565; 15.8152]	0.003
2	0.301±23.508	0,000 [-7,000 ; 8,000]	0.01	0.021±16.958	0.072 [-5.226 ; 5.1795]	0.01
3	6.555±22.363	6,000 [-1,000 ; 15,000]		0.114±17.265	0.168 [-5.442 ; 5.9771]	
4	2.746±28.446	3,000 [-9,000 ; 14,000]		0.109±22.754	0.046 [-9.315 ; 9.3571]	
5	7,594±22,797	8,000 [-8,000 ; 23,000]		0.157±20.380	0.295 [-13.037 ; 13.337]	0.03

6	0.252±52.626	0,000 [-13,000 ; 13,000]		0.044±27.092	0.038 [-7.973 ; 7.419]	0.01
7	6,568±40,157	6,000 [-7,000 ; 19,000]		0.250±22.565	0.298 [-8.702 ; 9.012]	
8	2,768±57,947	2,000 [-14,000 ; 19,000]		0.227±39.480	0.082 [-12.304; 11.921]	
9	7,169±52,618	6,000 [-28,000 ; 43,000]		0.289±47.846	1,343 [-31,774 ; 31,932]	0.05
10	0.325±230.841	1,000 [-53,000 ; 50,000]		0.236±185.208	0.282 [-40.511 ; 42.160]	0.01
11	6,593±319,779	3,000 [-51,000 ; 56,000]		0.196±270.363	2,135 [-49,789 ; 42,917]	
12	1,896±435,258	2,000 [-93,000 ; 100,000]		0.067±369.327	0.858 [-80.774 ; 82.479]	
13	7,171±53,116	7,000 [-31,000 ; 44,000]		0.026±48.130	0.649 [-34.573 ; 33.655]	
14	0.238±213.056	0,000 [-57,000 ; 61,000]		0.353±135.529	0.499 [-41.455 ; 41.035]	
15	6,704±205,719	7,000 [-48,000 ; 59,000]		0.422±142.680	0.362 [-41.742 ; 39.424]	
16	2,697±267,238	3,000 [-71,000 ; 76,000]		0.224±192.954	1,127 [-58,596 ; 58,658]	
17	7,115±74,329	7,000 [-44,000 ; 59,000]	0.007	0.344±67.582	0.123 [-45.765 ; 48.008]	0.004
18	0.188±198.178	0,000 [-60,000 ; 64,000]	0.01	0.310±129.497	1,217 [-47,301 ; 46,188]	0.01
19	6,623±180,076	6,000 [-57,000 ; 67,000]		0.819±128.028	1,921 [-47,825 ; 45,633]	
20	2,636±262,964	3,000 [-82,000 ; 93,000]		0.382±200.546	1,121 [-70,912 ; 73,355]	
21	6,845±90,523	10,00 [-56,000 ; 68,00]		0.315±81.506	2,608 [-56,710 ; 55,919]	
22	0.702±390.122	1,00 [-135,000 ; 126,00]		0.709±212.159	0.246 [-94.807 ; 90.669]	
23	5,066±404,508	3,00 [-116,000 ; 127,00]		0.547±322.293	0.600 [-91.822 ; 95.613]	
24	1,400±487,264	8,00 [-170,00 ; 177,00]		0.702±403.611	6,032 [-135,804; 145,13]	
p - value ***	$p < 0.05$					
Note. *p* - value * - the value of the Lilliefors criterion for noisy signals, *p* - value ** - the value of the Lilliefors criterion for the information component of signals, *p* - value *** - value of the Wilcoxon test for data between before and after treatment.						

Accordingly, the nonparametric Wilcoxon test was chosen for comparative analysis between the readings of noisy and filtered signals. In this analysis, if the p-value is the value of the Wilcoxon test. If $p < 0.05$, the hypothesis of a weakening of the noise interference components influence on the information signal is accepted, and the signals are distinguishable; if $p > 0.05$, the hypothesis is rejected. The results showed that the value of this criterion is less than the threshold of $p < 0.05$, which allows us to assert the presence of differences between the readings of noisy and filtered signals during the implementation of digital filtering.

It was previously noted in the report (Altay et all, 2025) that when conducting an AE diagnostic study of an OC, the main portion of the information signal is made up of interference, the energy of which is comparable to or higher than the energy of the information signal. Taking this into account, in this paper an assessment of the energy component of the signals under consideration, both information and interference, was carried out using the root mean square (*RMS*) indicator:

$$RMS = \sqrt{\frac{1}{N}(a_1^2 + a_2^2 + \ldots + a_q^2)},$$

where N is the number of signal samples, and a are the individual values of the signal sample up to q.

The value of this indicator can be interpreted as the instantaneous energy of the process generating the analyzed AE signal (Barat et all, 2010; Zakharov et all, 2022). The calculated values of this indicator for the information component of the signal and noise interference are illustrated in the Tukey diagram in Figure 5.

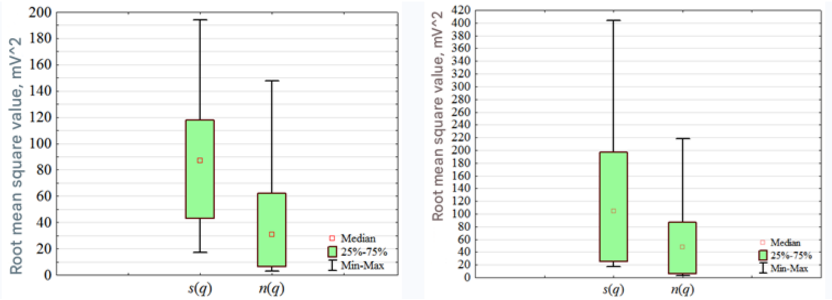


Figure 5. Tukey diagram representing the AE signal energy and interference during testing: *a*) a defect-free tool; *b*) a defective tool.

Comparing the processing results presented in Fig. 5, it can be seen that the amplitude of the information component $s(q)$ is 2 times greater than the amplitude of the noise component $n(q)$. When testing a defect-free instrument, the values of the median root mean square value of the information component were: $RMS_{Me} = 87.171$ mV^2; interference: $RMS_{Me} = 30.776$ mV^2. When checking a defective instrument, the values of the median root mean square value of the information component were: $RMS_{Me} = 104.756$ mV^2; noise interference $RMS_{Me} = 48.283$ mV^2. The obtained graphical results in Fig. 5a and 5b and the presented median values show that the energy of the information component of the signals is 2 times greater than the energy of the noise interference ($RMS_{s(q)} > RMS_{n(q)}$). This is also confirmed by the result of the frequency spectrum presented in Fig. 1, where the amplitude of the information component of the signal significantly exceeds the amplitude of the noise component.

Another criterion for assessing the comparability of the energy of the useful signal and interference is the experimental indicator of the signal-to-noise ratio (*SNR*), calculated as the ratio of the root-mean-square value of the signal to the root-mean-square value of the interference amplitude for the i -th signals under consideration at the output of the digital filter, as

$$SNR = 20\lg\left(\frac{s_i^2(q)}{n_i^2(q)}\right).$$

The calculated values of this indicator for signals obtained during testing of a defect-free and defective tool are illustrated in the Tukey diagram in Figure 6.

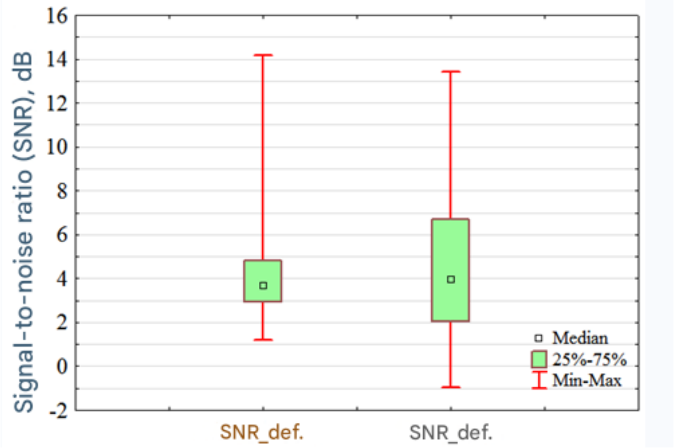


Figure 6. Acoustic emission signal to noise ratio.

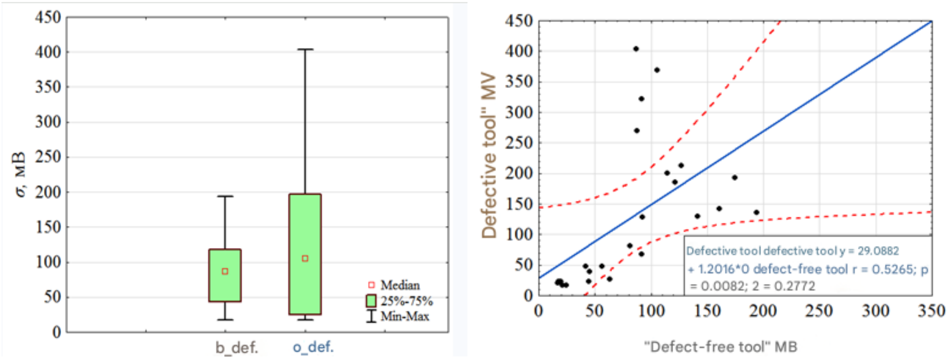
From the diagram presented in Fig. 6 it follows that the median SNR indicator during testing of a defect-free instrument was SNR $_{Me}$ = 3.661 dB, and during testing of a defective instrument – SNR $_{Me}$ = 3.931 dB. Values of the median SNR indicator above "0 dB" provide information on the excess of the amplitude of the information signal in relation to the amplitude of the interference. High values of this indicator characterize the stability of filters to influencing interference when implementing a polynomial digital filter. Based on the results of this assessment, further analysis of the parameters of the information component was carried out on the basis of calculating the secondary diagnostic indicators of AE.

Statistical evaluation of acoustic emission parameters. When evaluating signal parameters, the amplitude parameters describing the energy content of acoustic phenomena have the best correlation with the properties of the AE source assigned. To date, a significant number of specific statistical indicators have been used in works to evaluate the AE parameters. For this evaluation, such indicators as signal amplitude (U), signal peak-to-peak (between the maximum and minimum amplitude values, ΔU), root mean square deviation (RMS, σU), root-mean square signal value (U_{RMS}), and energy parameter (signal envelope area, MARSE) are often selected. Calculating the above parameters in order to detect statistically distinguishable but significant relationships between the parameters of a defective and defect-free instrument can be complex. In this regard, a joint evaluation of the above AE parameters is relevant.

The results of the correlation relationship assessment showed that there is a statistically significant correlation, different from zero, between the AE parameters during inspection of a flawless and defective tool. In the analyzed set of measurements, the highest correlation is observed for the parameter $r_{\text{peak-to-peak}} = 0.595$ when compared with the parameters $r_{\text{RMSE}} = 0.526$, $r_{\text{Amplitude}} = 0.527$, $r_{\text{RMS = 0.526}}$, $r_{\text{MARSE}} = 0.525$. Using the Chaddock rating scale for interpreting the correlation coefficient values, it should be noted that for the parameters r

$_{RMSE}$, $r_{Amplitude}$, $r_{peak\text{-}to\text{-}peak}$, r_{RMS}, r_{MARSE} There is a direct and noticeable ($r_{0.5\text{-}0.7}$) correlation relationship. The established correlation for these parameters at $r > 0.5$ is explained by the difference in the values of the parameters of the information component of the signals during testing of a defective and a flawless tool. Previously, it was noted that the parameters calculated in this article are stable interfering environmental factors and allow us to detect correlation relationships between the parameters of the AE source. In the framework of this study, when using the filter, statistically significant correlations of measurements ($p < 0.05$) were also found, characterizing the non-randomness of the obtained relationship. With the weakening of the interfering component, a high correlation of the measurement result, namely $r \sim 0.9$, can be observed when analyzing the information component recorded between paired AE signal converters from a single source.

A model characterizing the statistical distinguishability between the AE parameters during inspection of a flawless and defective tool was developed using a machine learning method – linear regression. Linear regression is an efficient and highly sensitive method to the analyzed data, requiring no special specific training of the samples of the test object. The conducted studies based on linear regression showed that among all the analyzed parameters (Begentayev et all, 2025; Begentayev et all, 2024), σ_U are sensitive to changes in the model of AE signal indicators during inspection of a defective tool (Altay et. all, 2025). These results are presented as a regression function and a Tukey diagram in Figures 8–10.



a) *b*)

Figure 8. Statistical distinguishability of the parameter σ_U: a) Tukey diagram characterizing the variability of the standard deviation of the signal amplitude when testing both instruments ; b) dependence characterizing the increase in the deviation of the signal amplitude when testing a defective instrument.

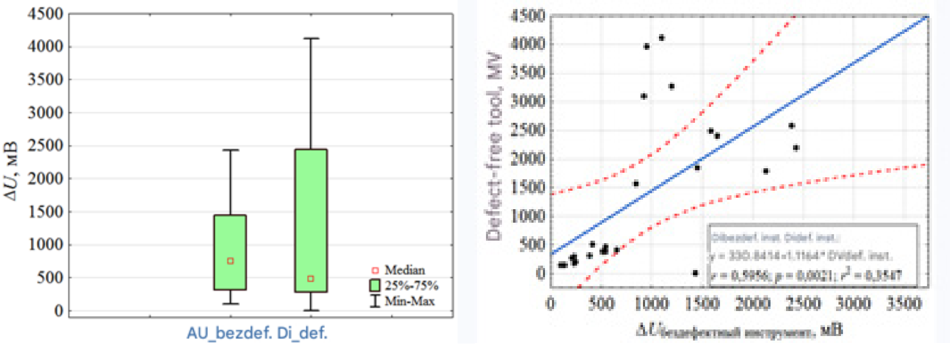


Figure 9. Statistical distinguishability of the parameter Δ *U*: a) Tukey diagram characterizing the variability of the signal amplitude range when testing both instruments;
b) dependence characterizing the increase in the signal amplitude range when testing a defective instrument.

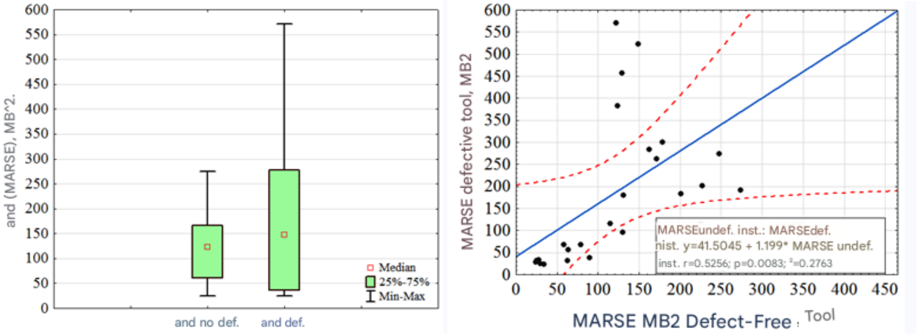


Figure 10. Statistical distinguishability of the MARSE parameter : *a*) Tukey diagram characterizing the variability of the signal energy value when testing both instruments;
b) dependence characterizing the increase in signal energy when testing a defective instrument.

To assess the adequacy of the constructed regression dependence, the coefficients of determination R^2 and correlation r were calculated, as well as significance p-level of the model:

$y_{\sigma,\ \text{defective tool}} = 29.088 + 1.201 \cdot \sigma_{\text{defect-free tool}}$ at $r = 0.526$, $R^2 = 0.277$, $p = 0.0082$;

$\Delta_{U,\ \text{defective tool}} = 330.841 + 1.116 \cdot \Delta_{U\ \text{defect-free tool}}$ at $r = 0.595$, $R^2 = 0.354$, $p = 0.002$;

$y_{MARSE,\ \text{defective tool}} = 330.841 + 1.116 \cdot MARSE_{\text{defect-free tool}}$ at $r = 0.525$, $R^2 = 0.276$, $p = 0.008$.

Following from the analysis of the data presented in Figures 8–10, there is also a direct noticeable correlation between the signal parameters during the inspection of a defective and a flawless tool. The value of the determination coefficient R^2 of the constructed model explains the observed dispersion of the predictor (the indicator in the focus of this study) during the inspection of a flawed tool. The obtained coefficients with a p - value less than for $p = 0.01$, and, therefore, are considered statistically significant for a confidence interval with a reliability of 0.99. That is, the associated AE parameters can be significant predictors of defect formation processes occurring in the tool with a reliability probability of the confidence interval. To date, the accumulated experimental material confirms the possibility of using the calculated parameters for predictive analytics (Altay, 2019) of the technical condition of the objects of inspection.

Conclusion. This article is devoted to the statistical evaluation of AE parameters during the implementation of a processing method based on bidirectional polynomial digital filtering. To validate the methods effectiveness, filtering results were obtained for recorded AE signals during milling with two tools. The distinguishability of the information component signals was demonstrated when compared with noisy signals ($p < 0.05$) using the Wilcoxon test, and the signal-to-noise ratio was calculated. Based on the obtained processing results, it was established that the AE processing method increases the signal-to-noise ratio to SNR = 4 dB and improves the filtering quality of high-frequency interference.

A correlation between the AE parameters during the testing of two instruments ($r > 0.5$ to $r = 0.7$) was established, indicating a direct and significant link between the measurement results. This correlation may be due to differences in the properties and characteristics of the AE sources during the testing of the two instruments for $p < 0.05$. Based on regression analysis, a model was developed characterizing the discriminability between the AE parameters during the testing of a flawless and a defective instrument, with statistical significance *at* $p < 0.01$.

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