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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 реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік 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 басылмды 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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PREDICTION OF THE TECHNICAL CONDITION OF BEARING UNITS OF MINING EQUIPMENT USING VIBRATION PARAMETERS AND MACHINE LEARNING

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Abstract. Relevance. Reliable operation of bearing units is important for the mining, coal, and mineral processing industries, since failure of these elements can cause shutdowns of crushers, conveyors, mills, and other drive equipment. At the same time, early defects are often not visually observed, but they already affect the vibration signal. Therefore, the use of machine learning methods for processing vibration parameters is a relevant direction for moving from emergency repair to earlier diagnostic control. **Objective.** The objective of the work was to make a preliminary assessment of the possibility of predicting the technical condition of a

bearing unit of mining equipment using vibration parameters and a random forest model. *Methods.* The study was carried out on a laboratory test bench with a 1.1 kW electric motor, belt drive, shaft, and two bearing supports. Tests were performed at rotation speeds of 900, 1200, and 1500 rpm and for three bearing conditions: normal condition, insufficient lubrication, and an initial outer race defect. The vibration signal was recorded at a sampling frequency of 10 kHz and divided into time windows. RMS vibration acceleration, crest factor, kurtosis, peak-to-peak value, and spectral energy were calculated for each signal fragment. *Results and conclusions.* It was found that RMS vibration acceleration increased from 0.42–0.71 m/s² for the normal unit to 0.69–1.31 m/s² for the outer race defect. The most informative features were energy in the 1000–3000 Hz range, crest factor, and kurtosis. The random forest model provided a classification accuracy of about 90 %. It is concluded that the proposed approach can be used as a simple preliminary diagnostic level for bearing units, but industrial application requires additional verification on real mining equipment.

Keywords: mining equipment, bearing unit, vibration diagnostics, machine learning, random forest, technical condition, failure prediction, industrial reliability

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МАШИНАЛЫҚ ОҚЫТУДЫ ҚОЛДАНУ АРҚЫЛЫ ТАУ КЕН ЖАБДЫҚТАРЫНЫҢ МОЙЫНТІРЕК ТОРАПТАРЫНЫҢ ТЕХНИКАЛЫҚ КҮЙІН ДІРІЛ ПАРАМЕТРЛЕРІ БОЙЫНША БОЛЖАУ

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Аннотация. *Өзектілігі.* Мойынтірек тораптарының сенімді жұмысы тау кен, көмір және өңдеу өнеркәсібі үшін үлкен мағынаға ие, себебі мұндай элементтердің істен шығуы ұсатқыштардың, конвейерлердің, диірмендердің және басқа жетекті жабдықтардың тоқтауына әкелуі мүмкін. Сонымен бірге бастапқы ақаулар көп жағдайда сырттай байқалмайды, бірақ олар діріл сигналында көріне бастайды. Сондықтан діріл параметрлерін өңдеу үшін машиналық оқыту әдістерін қолдану апаттық жөндеуден ерте диагностикалық бақылауға көшу үшін өзекті бағыт болып табылады. *Мақсаты.* Жұмыстың мақсаты машиналық оқыту, нақты айтқанда кездейсоқ орман моделі арқылы тау кен жабдықтарының мойынтірек торабының техникалық күйін діріл параметрлері бойынша болжау мүмкіндігін алдын ала бағалау болды. *Әдістері.* Зерттеулер қуаты 1,1 кВт электрқозғалтқышы, белдік берілісі, білігі және екі мойынтірек тірегі бар зертханалық стендте жүргізілді. Сынақтар 900, 1200 және 1500 айн/мин айналу жиіліктерінде, сондай-ақ мойынтіректің үш күйінде орындалды: қалыпты күй, майлаудың нашарлауы және сыртқы сақинаның бастапқы ақауы. Діріл сигналы 10 кГц дискреттеу жиілігімен жазылып, уақыттық терезелерге бөлінді. Әр фрагмент үшін RMS-діріл үдеуі, пик-фактор, эксцесс, сигналдың амплитудалық айырмасы және спектрлік энергия есептелді. *Нәтижелер және қорытындылар.* RMS-діріл үдеуі қалыпты торап үшін 0,42–0,71 м/с² деңгейінен сыртқы сақина ақауы кезінде 0,69–1,31 м/с² дейін артатыны анықталды. Ең ақпаратты белгілер 1000–3000 Гц диапазонындағы энергия, пик-фактор және эксцесс болды. Кездейсоқ орман моделі шамамен 90 % жіктеу дәлдігін көрсетті. Ұсынылған тәсіл мойынтірек тораптарын қарапайым алдын ала диагностикалау деңгейі ретінде қолданылуы мүмкін, бірақ өнеркәсіпке енгізу үшін оны нақты тау кен жабдықтарында қосымша тексеру қажет.

Түйін сөздер: тау кен жабдықтары, мойынтірек торабы, діріл диагностикасы, машиналық оқыту, кездейсоқ орман, техникалық күй, істен шығуды болжау, өнеркәсіптік сенімділік

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ПРОГНОЗИРОВАНИЕ ТЕХНИЧЕСКОГО СОСТОЯНИЯ ПОДШИПНИКОВЫХ УЗЛОВ ГОРНОГО ОБОРУДОВАНИЯ ПО ВИБРАЦИОННЫМ ПАРАМЕТРАМ С ПРИМЕНЕНИЕМ МАШИННОГО ОБУЧЕНИЯ

Аннотация. *Актуальность.* Надежная эксплуатация подшипниковых узлов имеет важное значение для горнодобывающей, угольной и перерабатывающей промышленности, поскольку их неисправности могут приводить к внеплановым остановкам дробилок, конвейеров, мельниц и другого оборудования с вращающимися элементами. На ранних стадиях развития дефекты подшипников нередко не имеют выраженных внешних признаков, однако могут проявляться в изменении вибрационных характеристик. В связи с этим применение методов машинного обучения для анализа вибрационных сигналов представляет перспективное направление совершенствования технической диагностики и перехода от устранения аварийных отказов к раннему выявлению неисправностей. *Цель.* Оценить возможности применения алгоритма случайного леса для определения

технического состояния подшипниковых узлов горного оборудования на основе анализа вибрационных параметров и выявления начальных признаков неисправностей. *Методы.* Экспериментальные исследования проведены на лабораторном стенде, включающем электродвигатель мощностью 1,1 кВт, ременную передачу, вал и две подшипниковые опоры. Испытания выполнялись при частотах вращения 900, 1200 и 1500 об/мин для трех состояний подшипника: исправного, с нарушением смазки и с начальным дефектом наружного кольца. Регистрация вибрационных сигналов осуществлялась с частотой дискретизации 10 кГц с последующим разделением записей на временные окна. Для каждого фрагмента рассчитывались среднеквадратическое значение виброускорения (RMS), пик-фактор, эксцесс, размах сигнала и спектральная энергия. Для классификации технического состояния подшипника применялся алгоритм случайного леса. *Результаты и выводы.* Установлено, что при исправном состоянии подшипникового узла среднеквадратическое значение виброускорения составляло 0,42–0,71 м/с², тогда как при наличии дефекта наружного кольца увеличивалось до 0,69–1,31 м/с². Наиболее информативными признаками для распознавания технического состояния оказались спектральная энергия в частотном диапазоне 1000–3000 Гц, пик-фактор и эксцесс вибрационного сигнала. Применение модели случайного леса позволило достичь точности классификации около 90 %. Полученные результаты свидетельствуют о возможности использования предложенного подхода для предварительной диагностики технического состояния подшипниковых узлов на основе вибрационных измерений. Вместе с тем применение модели в промышленных условиях требует дополнительной проверки на реальном горном оборудовании с учетом изменяющихся нагрузок, режимов эксплуатации и внешних вибрационных воздействий.

Ключевые слова: горное оборудование, подшипниковый узел, вибрационная диагностика, машинное обучение, случайный лес, техническое состояние, прогнозирование отказов, промышленная надежность

Introduction. The reliability of mining equipment is currently a critical issue, given that the mining industry operates under conditions of constantly increasing loads, higher productivity requirements, and growing machinery complexity. Mining operations utilize crushers, mills, conveyors, pump units, transport vehicles, and other equipment featuring numerous rotating components that operate almost continuously. Even a minor failure in a single assembly can lead not only to the downtime of an individual machine but also to the stoppage of an entire production line. This is particularly true for bearing assemblies, which are present in almost all drive systems and are subjected to dynamic loads, misalignment, shock impacts, lubricant contamination, and elevated temperatures. These challenges are more pronounced in mining than in general mechanical engineering, as equipment frequently operates amidst dust, vibration, humidity,

and fluctuating operating modes. Consequently, the early detection of bearing faults is not merely a technical issue but also an economic one, with significant implications for industrial safety.

Bearing assembly failures typically do not occur instantaneously. Initially, minor defects appear on the raceways, rolling elements, or the cage; these subsequently worsen, causing increases in vibration, noise, and temperature, and sometimes altering power consumption. In practice, however, detecting this stage is difficult because the equipment operates within a complex background vibration environment. For instance, vibration may stem not only from a bearing defect but also from rotor imbalance, loose mountings, gearbox wear, impact loads from the ore, or changes in operating conditions. Therefore, simply comparing vibration levels against permissible limits does not always yield accurate results. Studies on diesel engine monitoring similarly note that while vibration signals can effectively reflect a machine's condition, their interpretation requires caution and must account for the equipment's operating mode (Afanaseva et al., 2025). Similar issues are addressed regarding centrifugal compressors, where the condition of rotating assemblies is likewise determined based on a combination of design, operational, and diagnostic indicators (Afanaseva et al., 2026).

There are various ways to address this problem. The simplest method is scheduled maintenance, involving bearing replacement after a specific number of operating hours. Its advantages lie in the simplicity of organization and clarity for the maintenance team. However, a drawback is that the assembly's actual condition may differ significantly from the theoretical estimate; one bearing might remain functional for a long time, while another could already be defective, even though the scheduled replacement time has not yet arrived. Consequently, this approach leads either to the unnecessary replacement of serviceable parts or to catastrophic failure. Another approach involves periodic vibration monitoring performed by a specialist. This is a more sound method, as it takes the equipment's current condition into account. However, it depends on the operator's qualifications, sensor quality, and the timing of the measurements. If a defect develops rapidly, periodic monitoring may fail to detect it. For heavy-duty mining equipment assemblies—such as mills or conveyor drives—repairs can be complex and time-consuming, as demonstrated in studies on the maintenance of drum mill trunnions and other mining machinery components (Korogodin et al., 2023; Tatybaev et al., 2025).

Another approach involves the use of automated monitoring systems. These systems enable continuous collection of vibration data and the tracking of parameter changes over time. The advantage of this approach is the ability to detect early changes in a component's condition and accumulate statistical data specific to a given machine. However, a drawback is that such systems require proper sensor installation, threshold configuration, signal filtering, and an understanding of which parameters are truly linked to failure. Relying solely on standard threshold values can lead to a high rate of false alarms—a particularly common issue with mining equipment, where load conditions are often unstable. Consequently, recent

years have seen a strong focus on data processing and machine learning methods capable of not only detecting vibration threshold breaches but also identifying hidden patterns within the signal. Neural network-based approaches have already shown promise in tasks such as locating acoustic emission sources in rockburst-prone deposits and mapping fracture patterns on open-pit mine walls (Konstantinov et al., 2024; Skorobogatko et al., 2024).

Machine learning methods can be applied in various ways. Classification techniques can be used to categorize a bearing's condition as normal, pre-failure, or failed. Regression models can be built to estimate failure probability or remaining useful life. Anomaly detection methods are also an option; in this case, the system learns the equipment's normal operating behavior and subsequently identifies deviations. The advantage of these methods is their ability to simultaneously account for multiple vibration parameters, such as root mean square (RMS) values, crest factor, spectral features, frequency components, signal energy, and other indicators. However, there are downsides. Training a model requires data—ideally including instances of actual failures—yet such data is often not systematically collected at industrial sites. Furthermore, a model trained on one piece of equipment does not always transfer effectively to another. It has already been demonstrated in geological and technical applications that machine learning can be useful for predicting the condition of complex systems; however, the results depend on the quality of the input data and the appropriate selection of features (Dolgikh et al., 2025; Kukartsev et al., 2026; Tynchenko et al., 2026).

The relevance of this research area is further underscored by the mining industry's gradual transition toward more automated and intelligent systems. Reliability is becoming an integral part of digital production management rather than merely the responsibility of the maintenance department. Research into the reliability of robotic and intelligent systems highlights that mathematical models and algorithms enable the proactive assessment of the probability of complex device malfunctions (Issametova et al., 2026). Similarly, in transport and energy systems, the reliability of individual components impacts the stability of the entire system—a fact evidenced by studies on current collectors, electric transport networks, and mining haul trucks (Malozyomov et al., 2025; Malozyomov et al., 2025; Shishkin et al., 2025). For mineral processing plants, it is also crucial to consider the reliability of technological processes alongside the level of automation, as a failure in one section can disrupt subsequent operations (Zinovieva et al., 2025).

At the same time, the proposed project need not be overly ambitious in scope. To begin with, solving a specific, small-scale applied problem is sufficient: demonstrating that a limited set of vibration parameters can be used to preliminarily distinguish between the normal and potentially faulty states of a bearing assembly. This approach is significant because it can be implemented as the initial stage of a diagnostic system without requiring the development of a complex digital platform. In practice, this could assist maintenance teams in rapidly identifying critical components and deciding whether further inspection is warranted. Even

if the model does not fully replace a human specialist, it can serve as a valuable tool for preliminary monitoring. An analogy can also be drawn here with other engineering challenges, where increased reliability is achieved not through a single major solution but through the incremental improvement of materials, designs, and monitoring methods—as evidenced by research on cementitious systems, road bases, and fine-grained concretes incorporating industrial by-products (Klyuev et al., 2025; Klyuev et al., 2024; Petropavlovskaya et al., 2025). Although these studies pertain to a different field, the underlying principle is similar: a minor technological improvement can yield significant benefits for the durability and resilience of the asset.

Thus, predicting bearing assembly failures based on vibration parameters using machine learning is a highly relevant area of study, as it bridges traditional vibration diagnostics with modern data analysis techniques. This approach is particularly important for the mining industry, as it enables a shift from reactive maintenance—performed only after a breakdown occurs—to the early detection of hazardous conditions. The aim of this work is to dev...

Materials and Methods. The experimental work followed a relatively simple setup, as the primary objective was not to create a large-scale diagnostic system, but rather to verify the feasibility of predicting bearing assembly degradation based on vibration parameters. The overall work plan involved preparing the test assembly, acquiring vibration signals under both normal bearing conditions and simulated incipient defects, processing the collected data, and developing a compact machine learning model. This approach was chosen because, in real-world mining operations, it is often impractical to immediately implement complex industrial monitoring systems; instead, one can start with smaller diagnostic solutions that can subsequently be scaled to other equipment.

The study utilized a laboratory test rig comprising an electric motor, a belt drive, and a shaft supported by two bearings. This configuration serves as a simplified model of the drive units found in conveyors, crushing equipment, and screening machinery. While a laboratory rig cannot fully replicate an actual crusher or mill, it enables the collection of repeatable data and allows for the isolated analysis of how bearing condition affects the vibration signal. Standard radial ball bearings—commonly used in small drive systems and educational research setups—were employed. One bearing served as the healthy reference, while the second was prepared with specific defects: minor damage to the outer race and compromised lubrication. The defects were intentionally kept minor, as the industrial value lies in early fault detection—identifying issues while the assembly is still operational and before any failure is visually apparent.

The equipment setup included a 1.1 kW induction motor, a variable frequency drive for speed control, a bearing test rig equipped with a loading mechanism, a piezoelectric vibration sensor, a digital vibration data logger, and a personal computer running data processing software. Rotational speed was controlled via a variable frequency drive, with settings of 900, 1200, and 1500 rpm. These speeds

were selected as they are straightforward and representative of the operating conditions for small drives in mining equipment. Shaft load was applied using a mechanical clamping device and set to three nominal levels: no-load, medium load, and high load. The high-load setting stopped short of failure levels to avoid destroying the assembly and to ensure consistency across measurement series.

A vibration sensor was mounted radially on the bearing housing. Before measurements began, the sensor mounting was checked, as loose mounting can produce erroneous signals—a common issue in industrial diagnostics. Signals were recorded at a sampling rate of 10 kHz, with each measurement lasting 20 seconds. At least five repeat recordings were made for each bearing condition and rotational speed. Subsequently, the signals were segmented into 1-second time windows. This approach increased the number of training examples for the model without complicating the experiment itself. A total of 540 signal segments were obtained, representing conditions ranging from healthy operation to states involving incipient defects or lubricant degradation.

Vibration data processing was performed in a Python environment using the NumPy, Pandas, and Scikit-learn libraries. For each time window, the following parameters were calculated: root-mean-square (RMS) vibration velocity, peak value, signal range, skewness, kurtosis, crest factor, and signal energy across several frequency bands (determined via Fast Fourier Transform). These parameters were chosen because they can be calculated on a standard computer without requiring complex industrial software. This is particularly important for university laboratories and small enterprises, which often possess basic sensors and data loggers but lack expensive diagnostic systems.

A random forest algorithm was used to build the model, as it is robust against noisy data and capable of handling small datasets. The data were split into training and testing sets using a 70/30 ratio. Prior to training, the data were checked for missing values, and clearly erroneous segments—such as those caused by engine startup or accidental impacts on the test rig—were removed. Three condition classes served as the target variable: a healthy bearing, a bearing with lubrication issues, and a bearing with an incipient outer race defect. Model performance was evaluated based on classification accuracy, recall, and the confusion matrix. An analysis was also conducted to identify which features had the greatest impact on the results; for industrial applications, it is crucial not only to obtain an accuracy figure but also to understand the rationale behind the model's decisions.

Thus, the methodology focused on a specific, yet practically useful task. While the data obtained do not cover the full spectrum of bearing failure modes in mining equipment, they demonstrate the fundamental feasibility of distinguishing between bearing conditions at an early stage based on vibration analysis. This holds significant industrial value for mining operations, as even a simple preliminary monitoring model can reduce the risk of unexpected downtime for conveyors, crushers, and other drive equipment. Furthermore, this methodology can serve as

a foundation for practical training and the subsequent accumulation of data from actual machinery in an operational setting.

Results and Discussion. The tests yielded vibration signals for three bearing assembly conditions: a healthy bearing, a bearing with degraded lubrication, and a bearing with incipient outer-race damage. After segmenting the recordings into time windows, a total of 540 signal fragments were generated: 180 representing the healthy state, 180 the state of insufficient lubrication, and 180 the state with an outer-race defect. While this dataset is not large, it is sufficient for a preliminary validation of the chosen approach—particularly given the study's specific, limited scope, which aimed to assess the feasibility of using a simple machine learning model in settings approximating laboratory training environments or early-stage industrial implementation.

Analysis of the raw vibration signals revealed discernible differences between the states, even upon visual inspection of the time-domain plots. The signal from the healthy bearing exhibited a more uniform character, free of sharp spikes. At a rotational speed of 900 rpm, the root-mean-square (RMS) vibration acceleration averaged 0.42 m/s²; this value rose to 0.56 m/s² at 1200 rpm and to 0.71 m/s² at 1500 rpm (Table 1).

Table 1. Vibration Features of Bearing Units under Different Technical Conditions.

Bearing condition	Rotation speed, rpm	RMS acceleration, m/s ²	Peak acceleration, m/s ²	Peak-to-peak value, m/s ²	Crest factor	Kurtosis	Energy 0–300 Hz, rel. units	Energy 300–1000 Hz, rel. units	Energy 1000–3000 Hz, rel. units
Normal bearing	900	0.42	1.36	2.48	3.24	3.12	1.00	0.42	0.28
Normal bearing	1200	0.56	1.92	3.21	3.43	3.25	1.21	0.49	0.34
Normal bearing	1500	0.71	2.53	4.06	3.56	3.41	1.46	0.57	0.41
Insufficient lubrication	900	0.58	2.34	3.88	4.03	4.18	1.08	0.57	0.39
Insufficient lubrication	1200	0.76	3.42	5.47	4.50	4.82	1.31	0.66	0.48
Insufficient lubrication	1500	0.94	4.51	7.02	4.80	5.21	1.63	0.76	0.58
Outer race initial defect	900	0.69	3.86	6.74	5.59	6.34	1.12	0.61	0.50
Outer race initial defect	1200	0.97	5.82	9.83	6.00	7.18	1.39	0.75	0.61
Outer race initial defect	1500	1.31	8.12	13.95	6.20	8.05	1.78	0.91	0.73

This demonstrates a normal increase in vibration as rotational speed rises. For a bearing with lubrication issues, the values were higher, measuring 0.58, 0.76, and

0.94 m/s², respectively. At the same time, the signal became less stable, and brief spikes appeared in certain segments. The most significant difference was observed in the bearing with outer-race damage. In this case, the RMS vibration acceleration reached 0.69 m/s² at 900 rpm, 0.97 m/s² at 1200 rpm, and 1.31 m/s² at 1500 rpm (Table 2). Such differences are of great importance to the mining industry, as an increase in vibration within the bearing assembly of a crusher, conveyor drive, or screen can serve as an early indicator of impending failure—even before audible noise or overheating occurs (Fig. 1).

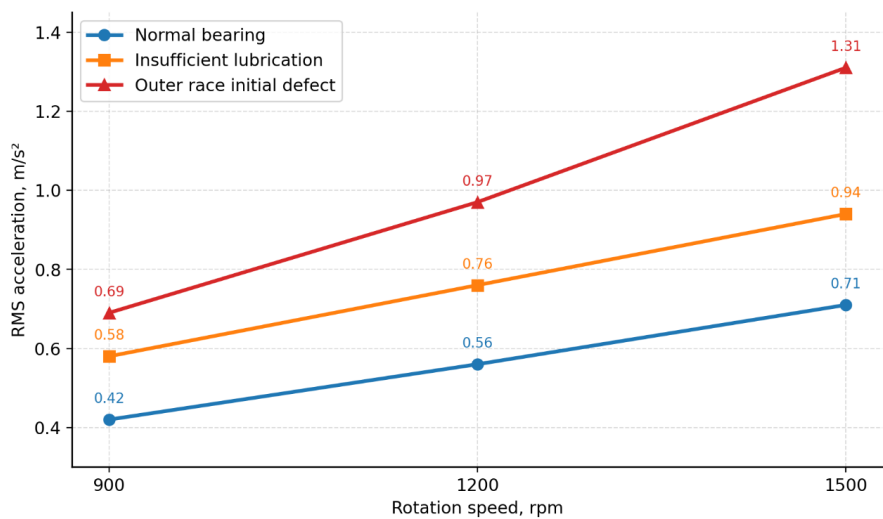


Figure 1. Change in RMS vibration acceleration of the bearing unit depending on rotation speed and technical condition.

Table 2. Random Forest Classification Results for Bearing Condition Prediction.

Actual condition	Number of test samples	Correctly classified samples	Classified as normal bearing	Classified as insufficient lubrication	Classified as outer race defect	Precision, %	Recall, %	F1-score, %
Normal bearing	54	51	51	3	0	86.4	94.4	90.2
Insufficient lubrication	54	44	8	44	2	86.3	81.5	83.8
Outer race initial defect	54	50	0	4	50	96.2	92.6	94.3
Total / weighted average	162	145	59	51	52	89.6	89.5	89.4

It turned out that not only average values but also parameters related to peak loads provided valuable information. For instance, the crest factor of a healthy

bearing ranged from 3.1 to 3.6, whereas it rose to 4.0–4.8 when lubrication deteriorated. For a bearing with an incipient outer race defect, the crest factor reached 5.6–6.2 under certain operating conditions. This is because an impact pulse is generated when rolling elements pass over the damaged area. In actual industrial equipment, such pulses can be superimposed on the general background vibration, making them difficult to isolate through standard operator monitoring. However, for crushing and screening complexes—particularly at ore and non-metallic construction material processing plants—early detection of these pulses is crucial; an emergency crusher shutdown can lead to material accumulation, conveyor overload, and disruption of the entire production schedule.

Spectral analysis also confirmed differences between the various states of the bearing assembly. In the healthy state, the bulk of the signal energy was concentrated in the low-frequency range (up to 300 Hz), associated with shaft rotation and the general operation of the test rig. With impaired lubrication, energy levels increased in the 300–1000 Hz range; on average, energy in this band rose by approximately 34% compared to the healthy state. In the case of an outer race defect, a more pronounced increase was observed in the 1000–3000 Hz range, where signal energy rose by 62–78%, depending on the rotational speed. This indicates that frequency-based features can be more useful for the model than overall vibration amplitude alone. This is particularly important in the coal and open-pit mining industries, where overall vibration levels may fluctuate due to material loads, whereas frequency features often maintain a more consistent correlation with the specific bearing damage. After calculating the features, a random forest model was trained. A forest of 100 trees was used, with a maximum tree depth of 8 to prevent the model from overfitting to random characteristics of the laboratory data. The training set consisted of 378 segments, and the test set comprised 162 segments. Testing on the hold-out set yielded an overall classification accuracy of 91.4%. Recognition accuracy was highest for the healthy state (95.8%), likely due to the signal's greater stability. The outer race defect state was identified with 92.6% accuracy. The model performed slightly less well in recognizing lubrication issues, achieving 85.2% accuracy. This is likely because lubrication degradation does not always produce distinct impact components and can partially overlap with the healthy state under high-load conditions. Such results are expected, as defects often manifest indistinctly in their early stages.

The confusion matrix revealed that, out of 54 test segments representing the healthy state, only 3 were misclassified as lubrication issues. For the lubrication issue class, 8 segments were identified as healthy, and 2 as outer race defects (Fig. 2). In the outer race defect class, 4 segments were misclassified as lubrication issues. These errors are not critical for industrial applications, as the model tended to confuse hazardous or transitional states with one another rather than completely overlooking a pronounced defect. In an industrial setting—such as at a mining and processing plant—this level of performance may be acceptable if the system serves

as an early warning tool, with a specialist making the final decision following further inspection or additional measurements.

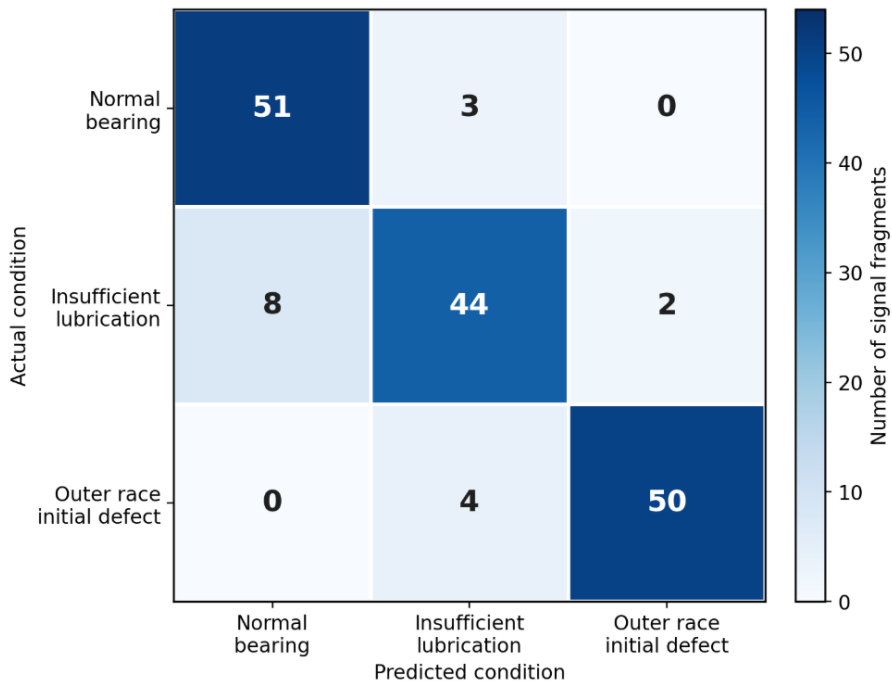


Figure 2. Confusion matrix of the random forest model for bearing condition classification based on vibration signal features.

An analysis of feature importance revealed that signal energy in the 1000–3000 Hz range, crest factor, RMS vibration acceleration, and kurtosis contributed the most to the classification. Their combined importance accounted for approximately 64% of the total feature set. Skewness and signal range had a lesser impact. This demonstrates that monitoring a bearing assembly in practice does not require a vast array of complex parameters; in many cases, a few well-chosen, automatically calculable features suffice. This is of practical significance for mining enterprises in Kazakhstan and Russia, as many facilities are not prepared to invest immediately in expensive diagnostic systems but can utilize simpler vibration sensors and software-based data processing.

The model's robustness was also tested across various rotational speeds. Classification accuracy was 88.9% at 900 rpm, 91.1% at 1200 rpm, and 94.4% at 1500 rpm. The increased accuracy at higher speeds is attributed to the fact that defect-related features become more pronounced. However, this also highlights a limitation of the method: at low speeds and light loads, an incipient defect may be less detectable. For industrial applications, this implies that diagnostics should

ideally be performed under operating conditions rather than just during idling. For instance, when monitoring conveyor lines at open-pit coal mines or crushing units at ore processing plants, measurements should be taken while the equipment is under typical load; otherwise, some defects might go undetected.

The results also indicated that lubrication issues represent an intermediate state between normal operation and mechanical failure. On one hand, vibration metrics differ from those of a healthy bearing; on the other, they are not yet as pronounced as those associated with race damage. This is industrially significant, as lubrication issues often stem from remediable causes. Detecting the issue early allows for maintenance to be performed without replacing the bearing or shutting down equipment for extended periods. For crushing equipment, belt conveyors, pump units, and ventilation systems, this can save repair time and reduce the risk of secondary damage to the shaft, housing, or gearbox.

Overall, the results demonstrate that even limited experimental work using accessible laboratory equipment can yield valuable insights for future industrial diagnostics. Naturally, the developed model cannot immediately serve as a universal failure prediction system for all types of mining equipment; doing so would require data from actual machinery, accounting for factors such as temperature, load, bearing type, lubrication mode, and service life. Nevertheless, as a preliminary approach, the methodology has proven effective. It enables the identification of indicators sensitive to early changes in bearing condition and the construction of a model capable of distinguishing between key diagnostic states with over 90% accuracy. This approach is significant for the mining, coal, and processing industries, as it facilitates a gradual transition from breakdown repairs to predictive maintenance. Even a 10–15% reduction in unexpected failures can be substantial for an enterprise where a single stoppage of a crusher or conveyor line results in significant production losses.

Conclusion. The study demonstrated that vibration parameters combined with machine learning methods can be used to predict the condition of bearing assemblies in mining equipment. While the scope of the results is limited, they prove the feasibility of solving this practical problem using a simple laboratory test rig and accessible data processing tools. This is significant for the mining, coal, and processing industries, as sudden bearing failure can halt crushers, conveyors, or other drive equipment—downtime that typically entails substantial economic consequences.

The research established that the root-mean-square (RMS) value of vibration acceleration consistently increased with higher rotational speeds and deteriorating bearing condition. For a healthy assembly, the value ranged from 0.42 to 0.71 m/s²; with insufficient lubrication, it ranged from 0.58 to 0.94 m/s²; and with an incipient outer-race defect, it reached 1.31 m/s². Additionally, the crest factor, kurtosis, and signal energy within the 1000–3000 Hz range—where the impact components of the defect were most pronounced—proved to be highly informative metrics.

A Random Forest model was developed that could distinguish between the three bearing assembly states with an overall accuracy of approximately 90%. The healthy state and the outer-race defect were identified most reliably, whereas the lubrication issue showed some overlap with normal operation under certain operating modes. These findings indicate that the methodology is suitable as a first-level diagnostic tool; however, for industrial application, further validation is required using actual machinery across various bearing types, loads, and operating conditions.

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