Vibration diagnostics of machine friction units: analysis of the current state and prospects

O. Lytvynov, O. Dykha[*]

Khmelnytskyi national University, Ukraine
*E-mail: tribosenator@gmail.com

Abstract

Vibration diagnostics makes it possible to detect defects in the friction parts of the machine at the early stages of their development, which provides for the repair or replacement of parts before they fail. In this work, an analysis of modern research on the use of vibration diagnostics in tribology is carried out, which includes aspects: vibration diagnostics in technology and tribology; vibration during friction and wear; vibration assessment methods; theoretical approaches in the analysis and modeling of vibrations. It is noted that an important aspect is the development and implementation of theoretical approaches in the analysis and modeling of vibrations, which allows a deeper understanding of the dynamics of friction and wear. This approach makes it possible to develop accurate and adaptive strategies for maintenance and optimization of tribotechnical parameters. It is shown that vibration diagnostics is not only a tool for detecting malfunctions, but also a key element for ensuring the long-term and efficient functioning of friction units of machines. The effective use of vibration diagnostics can significantly reduce maintenance costs, increase the reliability and productivity of equipment, which becomes an indispensable condition for the effective functioning of modern technical systems.

Key words: wear, friction details, vibrations, diagnosis, repair, forecasting

Introduction

Machine friction units make up no more than 5-7% of the mass of machines as a whole, it is minor changes in mass or physical and mechanical properties and geometric parameters of triboelements that cause up to 80% of all failures in the operation of machines and mechanisms. Agoone of the main directions of research is the study of friction, lubrication and wear of the surfaces of parts, as well as diagnosing their condition by various methods that are in a complex interaction. Currently, various methods are used to monitor the state of friction nodes, including vibration analysis, acoustic diagnostics, analysis of lubricants and wear products, and others. The application of vibration analysis is one of the most effective methods due to the simplicity of its implementation in online monitoring. However, it remains challenging to extract and process useful wear-related vibration signals and develop specific vibration-based indicators for wear characterization and monitoring. Combinationachievements of tribology and vibration mechanics opens up prospects for solving a number of topical problems related to increasing the wear resistance of contacting surfaces and reducing the level of vibrations in mechanical dynamic systems. In the context of optimizing the tribotechnical parameters of friction nodes, vibration diagnostics becomes an important tool for detecting and monitoring the condition of the equipment. An important direction in this topic is conducting experimental studies aimed at determining the relationship between contact interaction and tribological behavior of materials, taking into account the structure of vibrations. The basis for such research is a thorough substantiation of methods of processing vibration oscillations. This approach allows you to respond to different types of defects, such as cracks, wear, other damage or abnormal operating conditions.

Vibration diagnostics allows detecting defects in the early stages of their development, which allows repair or replacement of parts before they lead to serious breakdowns. Vibration monitoring helps determine optimal operating modes for specific friction assemblies, which can improve their service life and overall performance. Thanks to the early detection of problems, it is possible to avoid expensive repairs and save resources. Regular

monitoring of the state of friction nodes allows you to plan maintenance, avoid unexpected failures and reduce costs for scheduled maintenance.

In this work, an analysis of modern research on the use of vibration diagnostics in tribology is carried out, which includes: vibration diagnostics in technology and tribology; vibration during friction and wear; vibration assessment methods; theoretical approaches in the analysis and modeling of vibrations.

Vibration diagnostics in technology and tribology

Vibration diagnostics shows its importance in engineering and tribology - fields that investigate the interaction of friction, wear and lubricants. In the context of these industries, vibration diagnostics becomes not only a method of identifying problems, but also a tool for studying and optimizing tribotechnical parameters, ensuring stable and productive operation of equipment.

The following are the main stages of tool diagnostics in technology and tribology:

- inuse of vibration sensors to collect information about vibrations at various points of the equipment;

- Processing and analysis of collected data to determine frequencies, amplitudes and other parameters of vibrations;

-comparison of analysis results with standards to detect any abnormal deviations;

-determining the forecast of the technical condition and developing strategies for optimizing the parameters of friction nodes.

Machines generate vibration during operation, and unwanted vibrations occur that disturb the machine's system, resulting in malfunctions such as imbalance, wear, and misalignment. Thus, vibration analysis has become an effective method of monitoring machine health and performance. Machine vibration signals contain important information about the machine's condition, such as the source of the fault and its severity. Operators also receive early warning for scheduled maintenance. Over the years, numerous approaches to machine vibration data analysis have been proposed, and each approach has its own characteristics, advantages, and disadvantages. The article "Vibration analysis, practical control of machines for technological installations" [1] presents a systematic review of modern vibration analysis for machine monitoring and diagnostics. It involves data collection (applied tool such as analyzer and sensors), feature extraction and fault recognition methods using artificial intelligence. Answers to several research questions have been provided. A combination of time-domain statistical functions and deep learning approaches is expected to be widely used in the future, where fault characteristics can be automatically extracted from raw vibration signals. The availability of a variety of sensors and communication devices in new intelligent machines will be a new and huge aid to vibration monitoring and diagnosis.

Vibration and wear product analysis are the two main condition monitoring techniques for machine maintenance and fault diagnosis. In practice, these two techniques are usually performed independently and can diagnose only about 30-40% of faults when used separately. However, recent evidence shows that combining these two methods provides greater and more reliable information, resulting in a more efficient maintenance program with significant economic benefits to industry. Correlation of vibration analysis and wear residue analysis was investigated [2]. An experimental test bench consisting of a worm gear and driven by an electric motor was created to test the correlation of the two methods under different wear conditions. Three tests were performed under the following conditions: (a) no proper lubrication, (b) normal operation, and (c) presence of contaminants added to the lubricant. Oil samples and vibration data were collected regularly. Analysis of wear products included investigation of the number and size distribution of particles, investigation of morphology and particle types to determine possible wear mechanisms, and chemical composition analysis to assess the sources of wear. Fault detection in the vibration signature was compared to particle analysis. The results of this paper provided a better understanding of the dependent and independent role of vibration and wear product analysis in machine condition monitoring and fault diagnosis.

Smooth and trouble-free operation of electric motors is a requirement of modern industry. To ensure this, vibrodiagnostic is perfect. The study [3] analyzes the time and signal spectrum of the two most effective types of signals, i.e., vibration and current, for various electric motor faults. Analysis of the vibration and current signal (temporal and spectral) is performed using signals measured from various faulty electric motors from a laboratory setup. The advantages and disadvantages associated with these traditional procedures are shown. Next, existing research and development in the field of signal automation of condition monitoring methodologies for fault detection and diagnosis of various electrical and mechanical faults of electric motors is presented and summarized. Currently, artificial intelligence methods are used to diagnose malfunctions of electric motors and other machines. Advances in AI-based fault diagnosis, including popular approaches, are reviewed in detail. These methods are integrated with traditional monitoring methods. Overall, this article provides an overview of system signals, conventional and advanced signal processing techniques; however, it mainly covers the selection of effective statistical features, artificial intelligence techniques, and appropriate training and testing strategies for electric motor fault diagnosis.

Vibration damage detection has virtually no alternative for rotating steam turbine shafts during operation. To date, many vibration detection methods have been developed. But the effectiveness of all these methods depends very much on the type of structure, the way it is deformed and the type of damage. At the moment, practical engineers do not have a tool for correctly choosing the most suitable method of detecting damage to a

particular structure. Comparative evaluation of the effectiveness of different methods of vibration diagnostics for detecting damage up to a critical size is a complex and time-consuming process. Thus, a rather simple method of choosing the most effective vibration method of damage detection for a certain structure with a certain type of cracks and with a certain type of deformation was developed [4]. This method is based on determining the relative change in shaft compliance due to a crack using linear fracture mechanics. As an example, a comparative analysis of the sensitivity of several vibration detection methods to the presence of a longitudinal and transverse crack in the shaft during bending and torsional vibrations was carried out.

Wind power, which is one of the fastest growing sources of renewable energy, also has a high failure rate and O&M costs. Thus, condition monitoring and fault diagnosis of a wind turbine generator set are essential. Among the various components of a wind turbine generator set, the planetary gearbox plays a crucial role in the transmission and leads to a relatively higher failure rate and longer downtime. In this regard, a number of studies were published in academic journals and conference materials. The article "Vibration-Based Condition Monitoring and Fault Diagnosis of Wind Turbine Planetary Gearbox" [5] provides a systematic and relevant modern review of wind turbine planetary gearbox condition monitoring methods on the topics of fundamental analysis, signal processing, feature extraction, and fault detection. In addition, several valuable open questions are pointed out and potential research directions are suggested.

Having analyzed the articles [1-5], we have an intermediate conclusion that vibration diagnostics is an effective tool for improving the technical condition of friction units of machines. Timely detection of defects, optimization of work modes and cost savings make this method an integral part of tribotechnical management strategies. The use of vibration diagnostics allows you to maintain the equipment in an effective and reliable working condition, contributing to the extension of its service life and the reduction of maintenance costs.

Vibrations during friction and wear

In the process of friction and wear, vibrations occur, which can indicate various aspects of the technical condition of the equipment. Vibrations can occur due to uneven surfaces, improper lubrication, material defects, or malfunctions of friction units. Vibration diagnostics allows you to detect these vibrations and identify their sources.

Vibration analysis is a powerful diagnostic tool, and troubleshooting major technological mechanisms would be unthinkable without modern vibration analysis. There are many ways in which vibration data can be acquired and displayed to detect and identify specific problems in rotating machinery. By far the most important of these methods involve measuring vibration amplitude and frequency data. There are dozens of different data collectors and/or data collection modules available for this task.

The frictional force between sliding surfaces arises as a result of various and complex mechanisms and can cause undesirable dynamic characteristics of many mechanical systems. The laws of friction are phenomenological in nature because they are based on quantities that can be observed and measured. The mechanics of contact and friction of metal-metal and elastomer-metal contact surfaces are considered [6]. Unfortunately, there is no satisfactory method for determining or measuring the area of contact between sliding bodies. Both dry friction and lubricated friction are considered. Modeling the friction force in mechanical systems depends on several factors. These include material properties and geometry of sliding surfaces, surface roughness, surface chemistry, sliding speed, temperature, and normal load. Other factors include the effects of normal and tangential vibrations on static friction. Here, static friction is considered as a special case of kinetic friction. This basis is important for the study of friction-induced vibration.

Vibrations can directly affect the coefficient of friction. The change in the friction coefficient with a change in the vibration frequency and relative humidity on a mild steel disc was experimentally investigated[7]. The Pin-on-disc type apparatus is used for the experiment, which has the ability to vibrate the disc with different frequencies and amplitudes. During the experiment, the normal load, speed and relative humidity were varied. It was found that the coefficient of friction under conditions of no vibration is higher than under conditions of vibration, and the values of the coefficient of friction decrease with an increase in the frequency of vibration. Likewise, the friction coefficient decreases with increasing relative humidity. It was also observed that the rate of reduction of the friction coefficient has a certain relationship with the frequency of vibration and relative humidity.

The theory from the previous paragraph is confirmed by other studies [8]. The object of the study was the effect of external vibrations on the force of friction using different frequencies, amplitudes, loads and materials. The results show that it is possible to influence the force of friction between two contact surfaces using vibration. The force of friction can be weakened mainly due to separation of surfaces or increased by welding phenomena on contact surfaces. Experiments have shown that by changing one of the parameters, surface pressure, frequency or amplitude, it is possible to obtain either an increase or a decrease in frictional forces. Surface roughness, direction of vibration, relative velocity and materials can also play a determining role. Thanks to vibration support, the tendency to slip is reduced or eliminated.

Another study in this area provided new insight into the nature of the system's motion and the load–velocity–friction relationship. Thus, in the article [9], a tribological study of the macroscopic manifestation and characteristics of sliding friction was carried out. The aim of the task was to measure the friction in lubricated sliding contacts and to check the interaction between the environment (test stand) and the experimental friction

contact. Vibrations caused by friction were observed and studied as a manifestation of the process. The standard set of speed and force/torque sensors has been supplemented with a multi-channel vibration detection system. The operating modes of the system were identified using spectral analysis in confrontation with the natural vibration frequencies of the subsystems of the test stand.

Vibration assessment methods

There are several methods for evaluating vibrations in machine equipment. Among the most common are vibrometers (accelerometers), as well as the use of spectrum analyzers and filters for the selection of specific vibration components. Let's consider some real studies in this area.

Vibration-based structural performance monitoring methods are one of the most common approaches to structural damage identification. The presence of damage in structures can be determined by monitoring changes in dynamic behavior under external loading, and is usually performed using experimental modal analysis or operational modal analysis. These tools typically require a limited number of physically connected transducers (such as accelerometers) to record the structure's sensor parameters for further analysis. Sensors, wires, wireless receivers, and a data acquisition system are also typical components of traditional sensor systems. However, equipping lightweight structures with contact sensors such as accelerometers can introduce mass-loading effects, and for large-scale structures, instrumentation is laborious and time-consuming. Achieving high spatial resolution measurements for a large-scale structure is not always possible when working with traditional contact sensors, and there is also the potential for insufficient reliability associated with fixed contact sensors that will outlive the life of the main structure. Among the state-of-the-art non-contact measurements, digital video cameras are capable of rapidly collecting high-density spatial information from structures at a distance. In this paper, subtle motions from recorded video (i.e., image sequences) are extracted using Phase-based Motion Estimation (PME), and the resulting information is used to identify wind turbine damage. The PME and incremental motion-based approach estimates structural motion from a captured image sequence for both baseline and test cases of wind turbine blade damage. The operational deflection shapes of the test articles are also quantified and compared for the base and damaged states. Additionally, having adequate lighting can be a challenge when working with high-speed cameras, so image enhancement and contrast adjustments were also performed to improve the raw images. Ultimately, the selected resonant frequencies and deflection waveforms are used to detect the presence of damage, demonstrating the feasibility of implementing non-contact video measurements to perform realistic structural damage detection[10].

In the work "Method of visual characteristics of vibration for intelligent diagnosis of malfunctions of rotating machines" [11] a new method of diagnosis of malfunctions based on visual selection and characteristics of vibration is proposed. Instead of using conventional accelerometers to obtain fault data, the visual diagnosis method obtains full vibration information with rich vibration characteristics and does not create a mass load effect on the measured object. This method obtains time-domain vibration information from collected image sequences through image phase difference and then encodes it into grayscale images as input to a convolutional neural network model. Experimental test results on a bearing vibration image dataset show that the proposed method can achieve excellent performance in fault diagnosis. It provides excellent results with high classification and recognition accuracy.

The paper [12] provides an overview of the methods of vibration and acoustic measurements for detecting rolling bearing defects. Detection of both localized and distributed categories of defects is considered. The occurrence of vibration and noise in bearings is explained. Vibration measurements in both the time and frequency domains were considered, as well as signal processing techniques such as high-frequency resonance techniques. Other acoustic measurement methods such as sound pressure, sound intensity and acoustic emission were considered. Recent trends in bearing defect detection research, such as the wavelet transform method and automated data processing, have also been included.

The vibration diagnostics method is also used to monitor the state of ball bearings. Since the vibration graph reveals important information about the development of a defect in them [13]. Analysis of the time-domain vibration signature, such as peak-to-peak amplitude, rms, cross factor, and kurtosis, indicates ball bearing defects. However, these factors do not determine the position or nature of defects. Each defect causes a characteristic vibration in ball bearings. Therefore, the study of the vibration spectrum can provide information about the type of defects. In this article, a test bench was developed and a pair of brand new commercial ball bearings were installed. Bearings operate throughout their service life under constant speed and load conditions. During the test, vibration signatures are recorded and statistical indicators are calculated. When anomalies are detected in the statistical measurements, vibration spectra are acquired and examined to determine where the defect is located on the running surfaces. At the end of the test, the ball bearings are disassembled to take microscopic photographs of the defects.

For the quantitative diagnosis of rolling bearing malfunctions, a nonlinear vibration model was created in the study [14] to assess the severity of rolling bearing malfunctions. The defect size parameter of the outer ring is entered into the dynamic model, and the vibration response signals of the rolling bearings at different defect sizes are simulated. The signals are analyzed quantitatively to observe the relationship between vibration response and defect sizes. The points of impact, when the ball rolls on and away from the defect, are determined by the vibration

response signals. Next, the impact characteristic is obtained based on the time interval between the two impact points, which reflects the severity of the malfunction in the rolling bearings. When the bearing fracture width is small, the signals are presented as a distinct single shock. The signals gradually become double shocks as the size of the defects increases. The vibration signals of the rolling bearing test rig are measured for different sizes of damage to the outer ring. The experimental results are in good agreement with the simulation results. These results are useful for understanding the vibration response mechanism of rolling bearings under different fault severities.

From the articles [11-14], we can see that there are a large number of different methods of vibration assessment, from traditional vibrometer measurements to acoustic and photo observations. Each method has its advantages and disadvantages, but all of them are aimed at identifying and qualitatively assessing the condition of machines and mechanisms.

Theoretical approaches in the analysis and modeling of vibrations

The study and analysis of vibrations in machine equipment plays an important role in ensuring the reliability and productivity of technical systems. Theoretical approaches in the analysis and modeling of vibrations make it possible to understand the dynamics of the interaction of friction, wear and structural elements of equipment. In this article, we will consider the key aspects of theoretical approaches, their influence on the development of vibration diagnostics and the importance of improving tribotechnical parameters.

One of the main components of theoretical approaches is the development of mathematical models for describing vibrations in friction and wear systems. Models can include various factors such as stiffness, damping, mass, and other parameters that determine the dynamics of the system. The development of mathematical models makes it possible to accurately analyze various interactions and predict the behavior of systems in various conditions.

Analysis of deformations and stretching of materials allows to determine the influence of vibrations on structural components of machines and friction nodes. Dynamic systems study the interaction of objects taking into account temporal and spatial parameters, helping to build complex models of dynamics.

Consideration of tribological aspects is important for understanding the effect of friction and wear on vibrational dynamics. Modeling of tribosystems allows to analyze the effect of lubrication, properties of lubricants and other tribological parameters on equipment vibrations.

Theoretical approaches should always be accompanied by experimental confirmation. Real vibration data allow you to check the adequacy of mathematical models and improve them for more accurate forecasts and analysis of the influence of external factors. Let's consider several experimental studies on various equipment with the analysis of vibration oscillations.

In the work "Signal processing methods for estimating rolling bearing defects" [15], signal processing methods are proposed for selecting entry and exit points from the bearing vibration signal to estimate the size of the defect. The entry point is the starting point of the low-frequency response when the rolling element enters a localized defect in the raceway that is contaminated with background noise and difficult to identify. For effective identification of the entry point, a signal processing method based on an empirical model is proposed. A variational decomposition mode is applied to the bearing input signal for more accurate estimation. The differentiation technique is used to identify the high-frequency exit point with more reliable threshold values for automatic diagnosis. Then, based on the defect size estimation models for both the inner and outer ring defects, the defect size can be estimated. The proposed methodology is tested on the machine tool spindle bearing system. Experimental results show that the proposed signal processing methods provide less biased spindle speed results and more accurate estimation.

Time-frequency analysis can give a general idea of the behavior of friction-induced vibration. In the article [16], the short-time Fourier transform, the Wingner–Will distribution, the Choi–Williams distribution, and the Zhao–Atlas–Marx distribution are used to analyze the time-frequency characteristics of friction-induced vibration. The result shows that there is always a frequency change in the frequency-time representation of the vibration at the location where the vibration is confined. Frequency changes in time-frequency representations are related to the nonlinearity of vibration systems. The nonlinearity can be considered as evidence to support the idea that friction-induced vibrations are limited to limit cycles due to the nonlinearity of the system. On the basis of the frequency-time representation of oscillations, it can be concluded that the frictional vibration system is generally a linear system in the phase of vibration occurrence, but is a nonlinear system in the phases of limitation and disappearance of vibration.

Another model is proposed in the article "Damage diagnostics using time series analysis of vibration signals" [17]. It presents a novel time series analysis to identify the sources of damage in a mechanical system operating in various operating environments. The source of the damage is determined solely by analyzing the acceleration time history recorded from the structure of interest. First, a data normalization procedure is proposed. This procedure selects a reference signal that is "closest" to the newly obtained signal from an ensemble of signals recorded when the structure is undamaged. Second, a two-stage prediction model is built based on the selected reference signal (a combination of autoregression and autoregression methods with exogenous inputs. Then the residual error, which is the difference between the actual acceleration measurement for the new signal and the prediction obtained from the model developed on the basis of the reference signal, is defined as a damage-sensitive

function. This approach is based on the premise that if a structure has been damaged, a prediction model previously defined using an undamaged time history will not be able to reproduce the newly obtained time series measured from the damaged structure. Furthermore, increasing residual errors will be maximized on sensors installed close to the actual damage locations.The applicability of this approach is demonstrated using acceleration time histories obtained from an eight-degree-of-freedom mass-spring system.

The autoregressive model was studied in detail in the article "Non-stationary modeling of vibration signals for monitoring the condition of machines" [18] and the corresponding processes of feature selection and condition monitoring. For the analysis, an orthogonal transformation is introduced both to compress the features and to create a statistical model of the template representing the normal state. Finally, the measure of monitoring is determined using pattern recognition theory similarity analysis. An example of vibration monitoring of a reciprocating hydraulic pump shows how the proposed method can be used.

Another type is "Cyclostationary simulation of vibration signals". The study of [19] is to demonstrate that machine signals require special processing that is much more subtle than that of communication signals, from which the cyclostationarity paradigm originally arose and was developed for. First, different types of cyclostationarity are distinguished, covering many signals of a rotating machine. In particular, the importance of considering pure and not impure cyclostationarity is emphasized. Next, the relations between cyclostationarity of angle and time are investigated and some useful results are obtained. It is shown that the vibration signals exhibit cyclostationarity if and only if the random fluctuation of the machine speed is periodic, stationary or cyclostationary. As a result, a comprehensive methodology for the processing of actual cyclostationary signals is proposed: three typical examples are presented concerning the vibration signals of an internal coupling motor, a gearbox and a rolling bearing, each of which is characterized by a different type of cyclostationarity.

This theory is confirmed in the article "Cyclostationary processes: application in early diagnosis of malfunctions" [20]. It presents the theory of cyclostationary processes as a powerful tool for diagnosing rotating machines. It is shown that the well-known method of synchronized averaging is an expression of the first-order cyclostationarity, and the spectral correlation function obtained from the second-order cyclostationarity is an effective parameter for the early diagnosis of rotating machine faults. In addition, it is shown that the vibration signals measured on gear systems exhibit second-order cyclostationarity. The application for early diagnosis of chipping in gear teeth demonstrates the power of this new parameter.

Conclusions

1. At the current stage of development of the field of surface engineering, when technologies are developing rapidly and requirements for equipment reliability and productivity are constantly increasing, vibration diagnostics becomes a crucial element of strategies for managing the technical condition of machines and optimizing their tribotechnical parameters.

2. Directions for the use of vibration diagnostics for assessing the condition of friction units of machines are presented. It has been established that vibration diagnostics is an integral component of modern technical maintenance and management of machinery. The vibrodiagnostic technique allows for timely detection and analysis of various defects and anomalies in the operation of friction units, providing the possibility of preventing serious breakdowns and general improvement of machine reliability. Early detection of defects, optimization of operating modes and effective management of tribotechnical parameters make vibration diagnostics a necessary component to ensure the stability and efficiency of technical systems.

3. An important aspect is the development and implementation of theoretical approaches in the analysis and modeling of vibrations, which allows a deeper understanding of the dynamics of friction and wear. This approach makes it possible to develop accurate and adaptive strategies for maintenance and optimization of tribotechnical parameters.

4. It is shown that vibration diagnostics is not only a tool for detecting malfunctions, but also a key element for ensuring the long-term and effective functioning of friction units of machines. The use of this approach can significantly reduce maintenance costs, increase the reliability and productivity of equipment, which becomes an indispensable condition for the effective functioning of modern technical systems.

References

1. Jour Tang, Gang Mohd Ghazali, Mohamad Hazwan Rahiman, Wan Hindawi, Vibration Analysis for Machine Monitoring and Diagnosis: A Systematic Review 2021/09/11.https://doi.org/10.1155/2021/9469318

2. Z. Peng, N. Kessissoglou, An integrated approach to fault diagnosis of machinery using wear debris and vibration analysis, Wear, Volume 255, Issues 7–12, 2003, Pages 1221-1232, ISSN 0043-1648.https://doi.org/10.1016/S0043-1648(03)00098-X

3. Purushottam Gangsar, Rajiv Tiwari, Signal based condition monitoring techniques for fault detection and diagnosis of induction motors, Mechanical Systems and Signal Processing, Volume 144, 2020, 106908, ISSN 0888-3270.https://doi.org/10.1016/j.ymssp.2020.106908

4. AP Bovsunovsky, Efficiency analysis of vibration-based crack diagnostics in rotating shafts, Engineering Fracture Mechanics, Volume 173, 2017, Pages 118-129, ISSN 0013-7944. https://doi.org/10.1016/j.engfracmech.2017.01.014.

5.Hoon Sohn, Charles R Farrar, Damage diagnosis using time series analysis of vibration signals, 2001/06/01 https://dx.doi.org/10.1088/0964-1726/10/3/304

6.RA Ibrahim,Friction-Induced Vibration, Chatter, Squeal, and Chaos—Part I: Mechanics of Contact and Friction,Appl. Mech. Rev. Jul 1994, 47(7): 209-226 (18 pages). https://doi.org/10.1115/1.3111079

7.Mohammad Asaduzzaman Chowdhury, Md. Maksud Helali, The effect of frequency of vibration and humidity on the coefficient of friction, Tribology International, Volume 39, Issue 9, 2006, Pages 958-962, ISSN 0301-679X.

8. Thomas Skåre, Jan-Eric Ståhl, Static and dynamic friction processes under the influence of external vibrations, Wear, Volume 154, Issue 1, 1992, Pages 177-192, ISSN 0043-1648.https://doi.org/10.1016/0043-1648(92)90253-5

9.Łubiński, J., Druet, K., The Application of Vibration Recording and Analysis in Tribological Research on Sliding Friction, In: Timofiejczuk, A., Łazarz, BE, Chaari, F., Burdzik, R. (eds) Advances in Technical Diagnostics. ICTD 2016. Applied Condition Monitoring, vol 10. Springer, Cham. https://doi.org/10.1007/978-3-319-62042-8_19

10. Aral Sarrafi, Zhu Mao, Christopher Niezrecki, Peyman Poozesh, Vibration-based damage detection in wind turbine blades using Phase-based Motion Estimation and motion magnification, Journal of Sound and Vibration, Volume 421, 2018, Pages 300-318, ISSN 0022-460X. https://doi.org/10.1016/j.jsv.2018.01.050

11. Cong Peng, Haining Gao, Xiaoyue Liu, Bin Liu, A visual vibration characterization method for intelligent fault diagnosis of rotating machinery, Mechanical Systems and Signal Processing, Volume 192, 2023, 110229, ISSN 0888-3270. https://doi.org/10.1016/j.ymssp.2023.110229

12. N Tandon, A Choudhury, A review of vibration and acoustic measurement methods for the detection of defects in rolling element bearings, Tribology International, Volume 32, Issue 8, 1999, Pages 469-480, ISSN 0301-679X. https://doi.org/10.1016/S0301-679X(99)00077-8

13. Tuncay Karacay, Nizami Akturk, Experimental diagnostics of ball bearings using statistical and spectral methods, Tribology International, Volume 42, Issue 6, 2009, Pages 836-843, ISSN 0301-679X. https://doi.org/10.1016/j.triboint.2008.11.003

14. Lingli Cui, Yu Zhang, Feibin Zhang, Jianyu Zhang, Seungchul Lee, Vibration response mechanism of faulty outer race rolling element bearings for quantitative analysis, Journal of Sound and Vibration, Volume 364, 2016, Pages 67-76, ISSN 0022- 460X. https://doi.org/10.1016/j.jsv.2015.10.015

15. Aoyu Chen, Thomas R. Kurfess, Signal processing techniques for rolling element bearing spall size estimation, Mechanical Systems and Signal Processing, Volume 117, 2019, Pages 16-32, ISSN 0888-3270. https://doi.org/10.1016/j.ymssp.2018.03.006

16. GX Chen, ZR Zhou, Time–frequency analysis of friction-induced vibration under reciprocating sliding conditions, Wear, Volume 262, Issues 1–2, 2007, Pages 1-10, ISSN 0043-1648. https://doi.org/10.1016/j.wear.2006.03.055

17.Hoon Sohn, Charles R Farrar, Damage diagnosis using time series analysis of vibration signals, Smart Mater. Struct. 10 446, 2001/06/01 https://dx.doi.org/10.1088/0964-1726/10/3/304

18. Qi Zhuge, Yongxiang Lu, Shichao Yang, Non-stationary modeling of vibration signals for monitoring the condition of machinery, Mechanical Systems and Signal Processing, Volume 4, Issue 5, 1990, Pages 355-365, ISSN 0888-3270. https://doi.org/10.1016/0888-3270(90)90020-L

19. J. Antoni, F. Bonnardot, A. Raad, M. El Badaoui, Cyclostationary modeling of rotating machine vibration signals, Mechanical Systems and Signal Processing, Volume 18, Issue 6, 2004, Pages 1285-1314, ISSN 0888-3270 . https://doi.org/10.1016/S0888-3270(03)00088-8

20. C. Capdessus, M. Sidahmed, Jl lacoume, Cyclostationary processes: application in gear faults early diagnosis, Mechanical Systems and Signal Processing, Volume 14, Issue 3, 2000, Pages 371-385, ISSN 0888-3270. https://doi.org/10.1006/mssp.1999.1260.

Литвинов О.О., Диха О.В. Вібродіагностика вузлів тертя машин: аналіз сучасного стану та перспективи

Вібрайійна діагностика дозволяє виявляти дефекти деталей тертя машини на ранніх стадіях їх розвитку, що передбачає провадення ремонту або заміну деталей до того, як вони відмовлять. В даній роботі проведений аналіз сучасних досліджень застосування вібродіагностики в трибології, що включає аспекти: вібродіагностика в техніці і трибологіі; вібраціі при терті і зношуванні; методи оцінки вібрацій; теоретичні підходи при аналізі і моделюванні вібрацій. Зазначено, що важливим аспектом є розробка і впровадження теоретичних підходів при аналізі і моделюванні вібрацій, що дозволяє глибше розуміти динаміку тертя та зношування. Такий підхід дозволяє розробляти точні та адаптивні стратегії обслуговування та оптимізації триботехнічних параметрів. Показано, що вібродіагностика є не лише інструментом для виявлення несправностей, але і ключовим елементом для забезпечення тривалого та ефективного функціонування вузлів тертя машин. Ефективне застосування вібраційної діагностики може суттєво зменшити витрати на технічне обслуговування, підвищити надійність та продуктивність обладнання, що стає невід'ємною умовою для ефективного функціонування сучасних технічних систем.

Ключьові слова: зношування, деталі тертя, вібрації, діагностування, ремонт, прогнозування