Rolling Bearing Fault Detection in the Range of Ultrasound

Goran ŠINIKOVIĆ, Nenad GUBELJAK, Emil VEG, Mladen REGODIĆ, Darko JAGARINEC, Ivana MARKOVIĆ, Zorana JELI

Abstract: Acoustic signals have been used widely to detect the integrity of metal parts and the soundness of their contact. Diverse methods are developed to evaluate the actual quality of metal-to-metal contact having a lubricating layer. These methods are sensitive to the sound waves resulting from the sliding and rolling contact of the adjacent items. The ongoing research and operational experience created an effective and reliable method for acoustic detection of rolling bearing damage. Sound waves are detected by an appropriate transducer (sensor). The signal is processed, and the resulting root-mean-square (RMS) voltage is tracked. An increase in the voltage level indicates deterioration in bearing conditions. In practice, however, such an application almost always involves several considerations, including a significant amount of interfering background noises, unacceptable sound wave attenuations, and inaccessibility of the desired sensor locations.

Keywords: Rolling bearing damage, Early fault detection, Ultrasound emission

1 INTRODUCTION

Rolling bearings are one of the most critical components in rotating machinery. According to many studies [1], about 40% of failures of electric motors are caused by bearings. Therefore, bearings play one of the essential roles in condition monitoring.

Methods for bearing quality inspection and monitoring have been well-known for more than 40 years. World famous producers of vibro diagnostic equipment, SPM – Sweden, SKF – Sweden, SCHENCK – Germany, IRD – USA, developed their specific methodologies and instrumentation for rolling bearing early fault detection. All these methods are based on the vibration severity analysis in the common mechanical frequency range of 0 Hz to 20 kHz, and they have several limitations.

Unfortunately, a rolling bearing that lacks lubricant is a kind of hidden case from the aspect of vibrations. The vibration spectrum becomes significantly disturbed when the last drop of lubricant is lost.

The need for high reliability of industrial machines dictates a substantial effort to reduce downtime. Early detection of possible failure is of crucial importance for the protection of system integrity.

The idea of ultrasonic detection of machine conditions is a well-known approach. The methodology of signal refinement to a valid assessment of rolling bearing conditions and appropriate state prediction is still an innovative study.

This article describes the system's requirements, where the analysis of the bearing condition and its diagnosis are performed locally by an embedded sensor placed near the monitored motor.

2 MEASUREMENT METHODOLOGY
2.1 High-Frequency Vibration – ultrasound

Bearings, good or bad, new or old, produce ultrasonic friction as the internal rolling elements turn against the inner and outer raceways. A good bearing will produce less acoustic energy than a bearing with typical wear flaws such as pitting, spalling, flattening of the balls and scarring of the raceway. Likewise, the friction-absorbing properties of grease mean a well-lubricated bearing produces less friction than a bearing that lacks lubrication. As a lubricant's viscosity deteriorates and/or the bearing's

material composition stresses and fatigues, the friction and the corresponding ultrasonic emissions increase. Monitoring and trending high-frequency bearing energy allows us to determine proper lubrication intervals and predict when the bearing enters its first stages of wear.

Airborne and structure-borne ultrasonic inspection represents a trending technology with a long resume of versatile applications for predictive maintenance, reliability, facility management and lubrication. More recent technological advancements have expanded the uses for airborne and structure-borne ultrasound to include Acoustic Vibration Monitoring (AVM), which encompasses condition monitoring of rotating equipment, general predictive maintenance inspections of production machinery and lubrication scheduling [3–6]. Some of those improvements include enhanced accuracy and repeatability, built-in route capable data collectors, and the addition of multi-functional applications and sensors for applying lubrication to bearings' rolling elements.

Ultrasound is defined as sound waves having a frequency above the limits of human hearing, or above 20,000 Hz. So, by definition, ultrasound is undetectable by human ears unless aided by instruments capable of converting ultrasound to audible sound.

The energy of a sound wave diminishes the further it travels from its source. Because sound waves spread out in widening spheres, their energy is dispersed over a large area. This phenomenon is known as attenuation. Audible sound will propagate further and broader than ultrasound with the same energy, because an audible sound wavelength is much longer than an ultrasound wavelength [7–13]. For this reason, ultrasound is more directional to its source than lower frequency audible sounds. The directional characteristics of ultrasound allow a high-frequency phenomenon that is localised to its source to be detected without the interference of parasite vibrations. This directional characteristic makes it easy to pinpoint the exact source of bearing defects and lubrication failure in rolling element bearings in very loud and noisy environments [14].

Acoustic emission measurement (ultrasound levels) and vibration analysis are very similar methodologies that provide entirely different information. Measuring vibrations in the low-frequency domain (vibration speed and displacement) can indicate mechanical problems such as imbalance, misalignment, etc. With this method,

detection of bearing defects is only possible in the later stage of bearing failure, which shortens the time for planning machine overhaul significantly.

On the other hand, measuring vibrations in the high-frequency domain (acoustic emission) enables monitoring the entire evolution of the bearing, determining optimal lubrication intervals, the required amount of lubricant, and detecting the first signs of a bearing being damaged.

2.2 Signal Processing

The ultrasonic transducer (Fig. 1) used in the experiment uses sensors (Fig. 2) with piezo-electric quartz crystals excited by the energy of high-frequency acoustic vibrations.

Figure 1 Ultrasonic transducer

Figure 2 Ultrasonic sensor

The sensor measurement range is from 100 to 500 kHz. The optimal range in bearing detection is in the range of 100 – 250 kHz. A custom bandpass filter was created precisely according to this characteristic. It practically suppresses all signals below 100 kHz and above 250 kHz. The electronic module also provides a gain of 24 dB and a low output impedance. A 9V battery is used to minimise interference from the power supply, providing more than 4 hours of autonomy. The electronic module has high-quality, low-noise operational amplifiers NE5532 and NE5534. They are characterised by a noise density at the input of 5nV/√Hz and a GBW (Gain Bandwidth Product) of 10 MHz.

The filter design is simulated by LTSpice simulator software. It is based on the 4th order Butterworth filter, designed to have a flat frequency response in the bandpass.
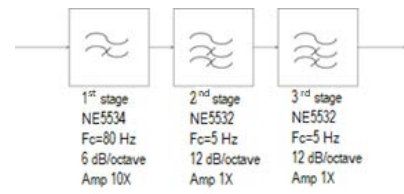

Figure 3 Amplifier block diagram

The realised amplitude characteristic was measured. A maximum 24 dB per octave slope was observed in the range from 1200 Hz to 4000 Hz, which then changed to a slope of 12 dB per octave up to 12 kHz.
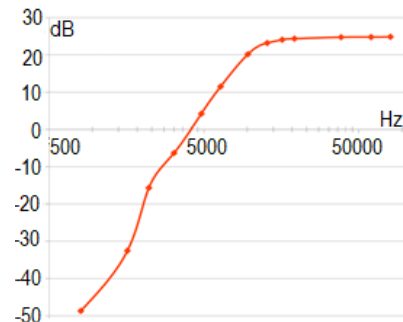

Figure 4 The transfer characteristic of the high-pass filter

In addition to the bandpass filter, the analogue block supplies the sensor with a special "Current pump diode", limiting the supply current to 4.3 mA. Upon output from the analogue block, the signal is forwarded to a digital oscilloscope (Fig. 5), which records a time signal with a defined record density. The degree of damage to the tested bearing is assessed, based on the image of the recorded signal in the ultrasound domain.
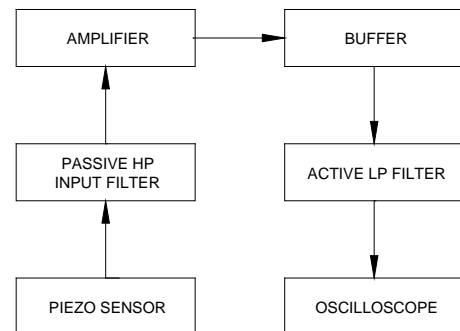

Figure 5 Block diagram of signal processing

2.3 Criteria for assessing the condition of a bearing

Setting a general criterion for bearing condition assessment based on ultrasound emission measurement is too ambitious a request. The realistic goal is to establish a series of criteria for different types and dimensions of bearings, where the general rule will be the same, and will be based on the logarithmic value of the relative ratio of the emission energy of the reference bearing (a new one) and the one being tested. Through experimental testing, it was determined that the following equation could represent the optimal form for quantification of ultrasound emission:

$$USE = 20\log\frac{v_{max}}{v_{ref}} - 10 \qquad (1)$$

USE – Ultra Sound Emission

It was determined experimentally that the optimal value of the reference voltage is 10 mV.

The constant in the equation depends on the bearing type, and translates the output value from equation (1) into a corresponding reference domain; green – good, yellow – acceptable, red – unacceptable. The values given by equation (1) are realistic, and represent a recognisable indicator of multiple times increased noise in the case of a damaged bearing.

The parameter determined for the assessment of the condition of the bearing by the ultrasound emission measurement method is USE. Limit values for condition assessment were determined, based on tests performed on bearings with different degrees of damage, and they are shown in Table 1.

Table 1 Threshold values for bearing condition assessment by measuring ultrasound emission (USE)

USE	Bearing condition
0 – 7.5	Good
7.5 – 17	Acceptable
> 17	Unacceptable

3 TEST AND VERIFICATION
3.1 Test rig

The experiment was conducted using a bearing test rig which comprised an AC motor and a shaft supported by one journal bearing and one rolling bearing, which was the test bearing.
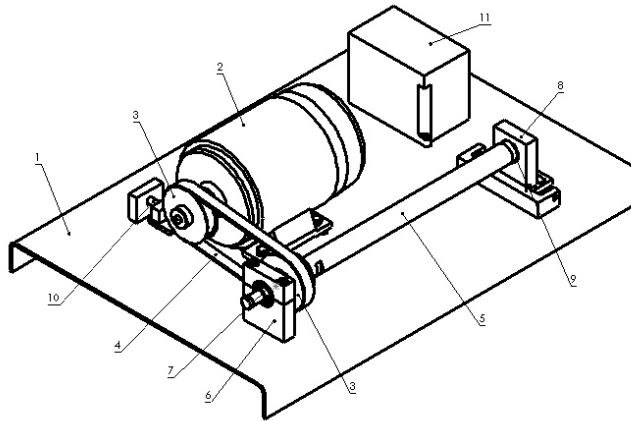
Figure 6 Test Rig drawing

The main parts of the device (Fig 6) are:
1. Base plate
2. AC motor
3. Pulleys
4. Timing belt
5. Shaft
6. Rolling bearing housing
7. Rolling bearing (tested bearing)
8. Journal bearing housing
9. Journal bearing
10. Tensioner
11. Mini frequency converter

An ultrasound transducer is located on the bearing housing. The device simulates the radial load, misalignment and inadequate internal clearance.

Radial bearing load is achieved using a special tensioner and sliding guides. It is possible to simulate the linear displacement of an electromotor during tension and keep the axes in a parallel position.
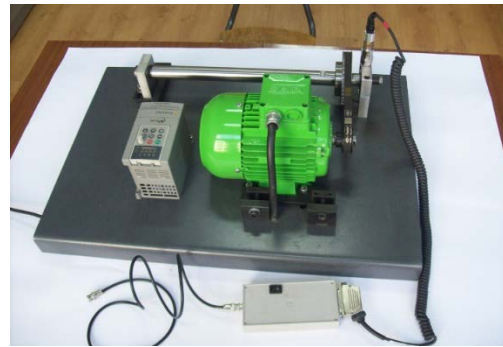
Figure 7 Test Rig

Simulation of a misaligned bearing is performed by moving the back support in the perpendicular direction (Fig 8). This support of the shaft is a journal bearing to eliminate surrounding noise during the measurement.
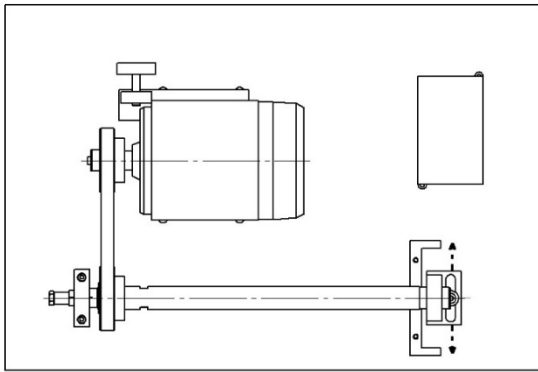
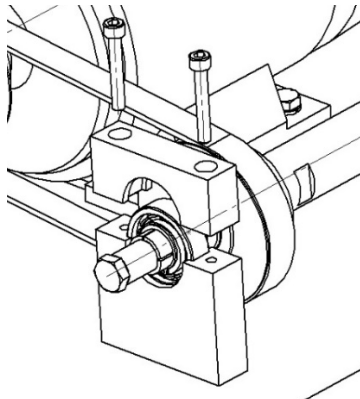Figure 8 Simulation of bearing misalignment

Figure 9 Construction of the bearing housing

The connection of the inner ring of the bearing and shafts is established through a specially designed split shaft cone. This solution allows for easy assembly and disassembly of the bearing on the shaft (Fig. 9). On the other hand, a controlled tightening screw generates a force transmitted over the cone on the inner ring of the bearing. This way, it is possible to realise the inner ring's strain and reduce the internal clearance.

3.2 Measuring procedure

The experiment was conducted using three standardised techniques of a reputable manufacturer and an originally developed methodology for rolling bearing fault detection:

- Enveloped Acceleration (by SKF) [15]
- Shock Pulse Meter (by SPM) [16]
- Level of Vibration (ISO 10816) [17]
- Ultrasound Emission (USE)

The measurement parameters and limit values for the standardised methods are shown in Table 2.

Table 2 Threshold values for bearing condition assessment

SPM	ENV	LoV	Stand. Methods
	a_{ENV}	v_{RMS}	Measur. Value
dB_N	gE	mm/s	Measur. Unit
< 20	< 0,75	< 0,7	Good
20 – 35	0,75 - 2	0,7 – 1,8	Satisfactory
	2 - 4	1,8 – 4,5	Unsatisfactory
35 – 60	4	> 4,5	Unacceptable

ENV – Enveloped Acceleration (by SKF)
SPM – Shock Pulse Meter (by SPM)
LoV – Level of Vibration (ISO 10816)

The experiments utilised bearings used in the conveyor belts' rolls in the surface mine "Kostolac", Serbia. All bearings were of the same type (6306), by different manufacturers and at different stages of damage (Fig. 10).
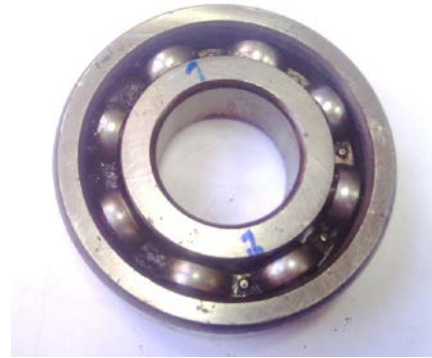

Figure 10 Tested Bearing (6306)

4 RESULTS

The test was performed on 15 bearings of the same type with different degrees of damage. Before the test, all the bearings were marked with numbers from 1 to 15. Table 3 shows the results with condition assessment for four different measurement methods.

Table 3 Measurement Results

No	Measuring Methods	Value	Bearing Cond.	
1	LoV.	1.6 mm/s	Good	
	Env. Acc	0.6 gE	Good	
	SPM	12 dB	Good	
	USE	5.4	Good	
2	LoV	7.9 mm/s	Unaccept.	
	Env. Acc	12 gE	Unaccept.	
	SPM	60 dB	Unaccept.	
	USE	30	Unaccept.	
3	LoV	5.6 mm/s	Unaccept.	
	Env. Acc	5.0 gE	Unaccept.	
	SPM	35 dB	Unaccept.	
	USE	17.7	Unaccept.	
4	LoV	2.2 mm/s	Unsatisf.	
	Env. Acc	1.2 gE	Satisfa.	
	SPM	22 dB	Satisfa.	
	USE	7.2	Good/Satisfa.	
5	LoV	1.9 mm/s	Unsatisfa.	
	Env. Acc	0.5 gE	Good	
	SPM	27 dB	Satisfa.	
	USE	8.1	Satisfa.	
6	LoV	1.9 mm/s	Satisfa.	
	Env. Acc	0.6 gE	Good	
	SPM	10 dB	Good	
	USE	5.7	Good	
7	LoV	2.6 mm/s	Unsatisfa.	
	Env. Acc	0.7 gE	Good	
	SPM	20 dB	Good	

	USE	6.2	Good	
8	LoV	2.2 mm/s	Unsatisfa.	
	Env. Acc	1.6 g$_E$	Satisfa.	
	SPM	22 dB	Satisfa.	
	USE	5.7	Good	
9	LoV	2.2 mm/s	Unsatisfa.	
	Env. Acc	0.5 g$_E$	Good	
	SPM	14 dB	Good	
	USE	4.5	Good	
10	LoV	2.9 mm/s	Unsatisfa.	
	Env. Acc	4.3 g$_E$	Unsatisfa.	
	SPM	28 dB	Satisfa.	
	USE	10.9	Satisfa.	
11	LoV	2.4 mm/s	Unsatisfa.	
	Env. Acc	2 g$_E$	Satisfa.	
	SPM	25 dB	Satisfa.	
	USE	10.3	Satisfa.	
12	LoV	1.9 mm/s	Good	
	Env. Acc	0.6 g$_E$	Good	
	SPM	14 dB	Good	

	USE	4.8	Good	
13	LoV	2.3 mm/s	Unsatisfa.	
	Env. Acc	2.5 g$_E$	Unsatisfa.	
	SPM	25 dB	Satisfa.	
	USE	11.7	Satisfa.	
14	LoV	1.9 mm/s	Good	
	Env. Acc	0.8 g$_E$	Good	
	SPM	20 dB	Good	
	USE	7.6	Good/Satisfa.	
15	LoV	2.1 mm/s	Unsatisfa.	
	Env. Acc	0.8 g$_E$	Good	
	SPM	14 dB	Good	
	USE	5.2	Good	

Figure 11 is a graphic representation of the assessment of the bearing condition based on four different testing methodologies. Bearing number 2 is not shown, because the measurement values are extremely high and out of the display range.
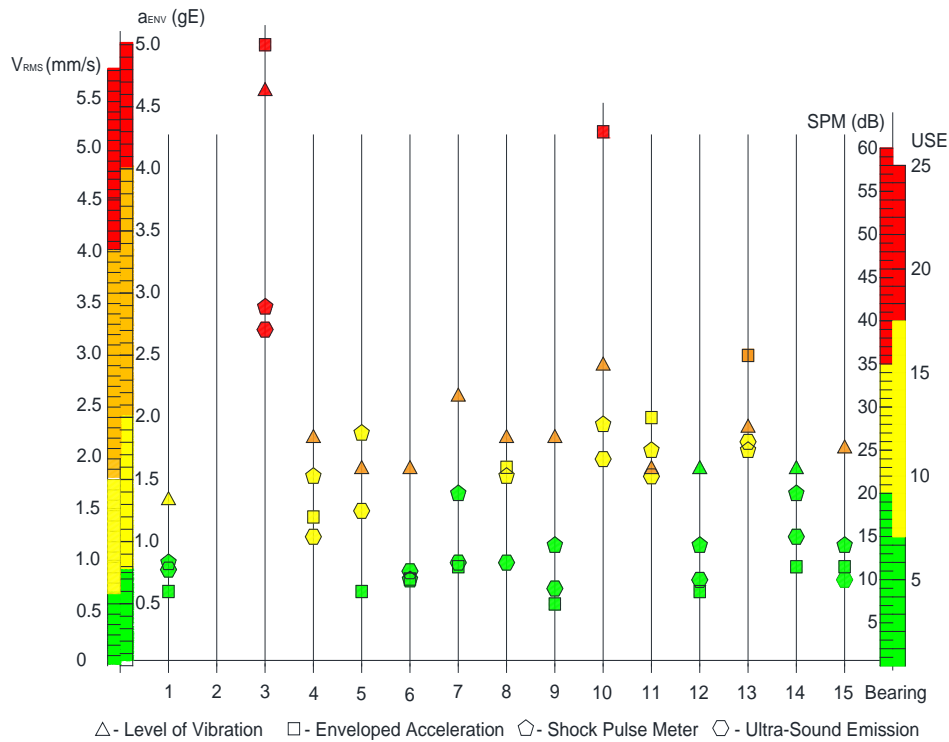

Figure 11 Comparative display of the condition assessment

The diagram shows the remarkable alignment of the ultrasound emission measurement method (USE) results with the results of other standardised methods. There are discrepancies in the assessment when comparing the results obtained by the vibration level measurement method and other advanced methods for assessing the condition of the bearing. This is because measuring the vibration level cannot determine the condition of the bearing reliably, because the total vibration level also includes signal components that do not originate from damage to the bearing (signal components at lower frequencies). Figures 12, 13, and 14 show the vibration spectra for bearings nos. 6, 9, and 13 with the most significant deviations. The images show that the main components of the signal are in the low-frequency zone, which means that they do not originate from bearing damage.
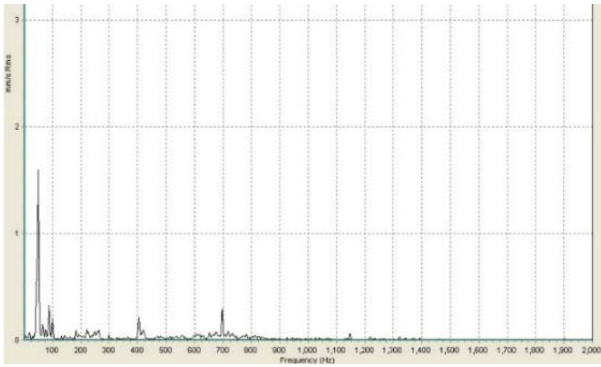
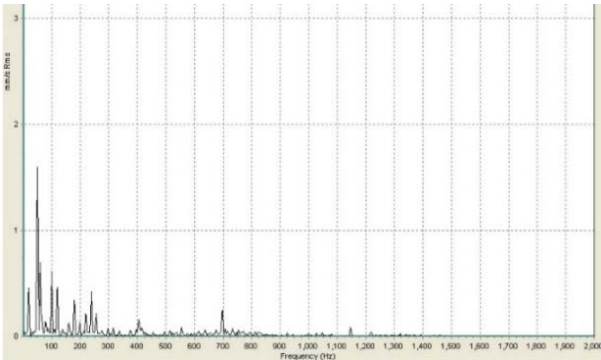Figure 12 Spectrum of vibration for Bearing 6

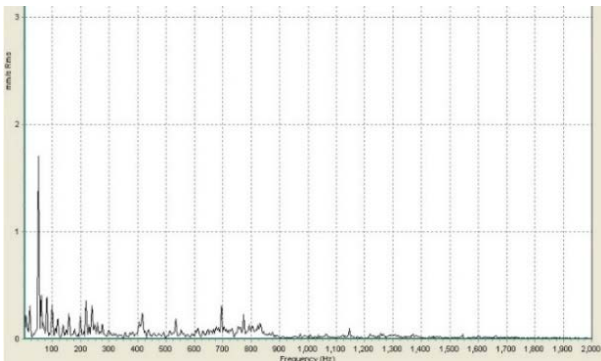Figure 13 Spectrum of vibration for Bearing 9

Figure 14 Spectrum of vibration for Bearing 13

Figures 15, 16 and 17 show the ultrasound emission (USE) signal for the mentioned bearings. The diagrams show that the level of ultrasound emission is rather low, which indicates that the bearings are in good condition.
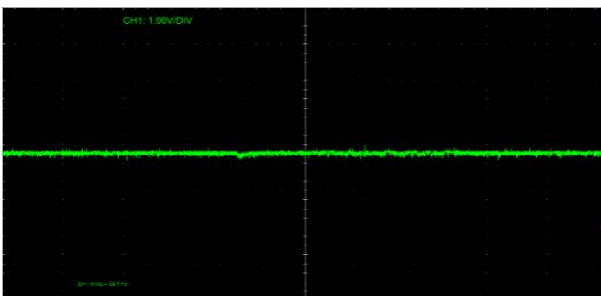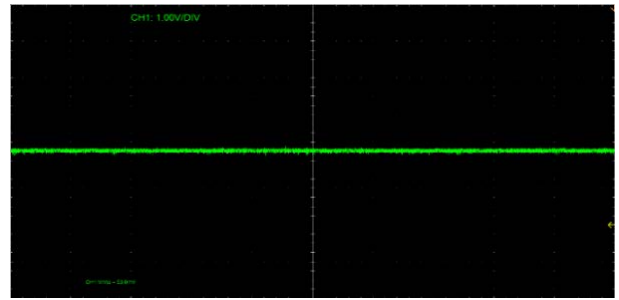

Figure 15 Signal of USE for Bearing 6

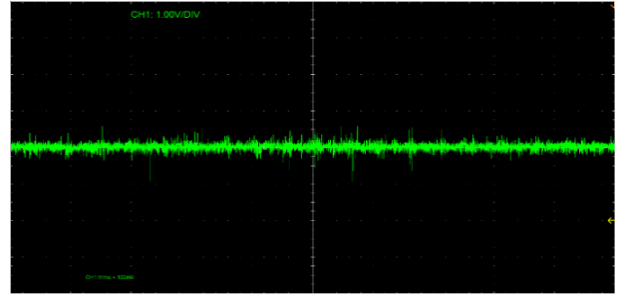Figure 16 Signal of USE for Bearing 9

Figure 17 Signal of USE for Bearing 13

An example of a USE diagram for a damaged bearing is presented in Figures 18 and 19.
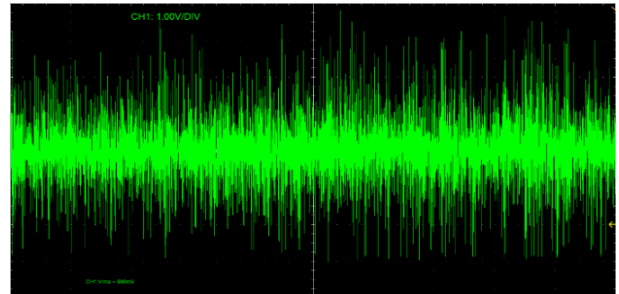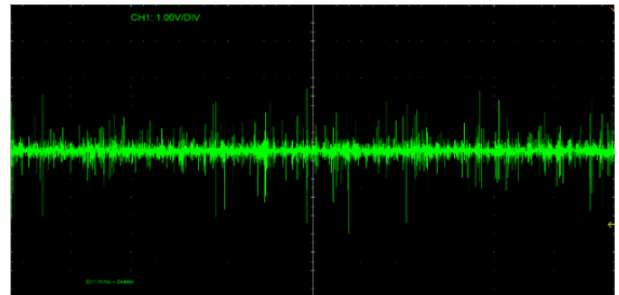

Figure 18 Signal of USE for Bearing 2

Figure 19 Signal of USE for Bearing 3

An extremely high level of USE can be observed on these bearings, indicating significant damage.

5. CONCLUSION

The paper provides an original methodology for detecting rolling bearing damage in the ultrasound domain. It presents an applicable model and a prototype solution of an electronic block for conditioning source signals. A simple formulation of the quality criteria is given, allowing for essential comprehension and differentiation of dissipated energy due to damage, both in the early and advanced stages of damage.

A commercial application can be developed and implemented in diagnostic equipment for vibro diagnostics and bearing damage detection based on a clearly formulated methodology.

The laboratory testing included testing bearings with different degrees of damage and in different operating modes, with a digital record of the collected emitted acoustic signal. The signal was analysed in the Time and Frequency domain, with the optimal frequency range found, representing the condition of the rolling bearing in the best way.

A valid comparison and setting of the necessary parameters for a harmonised assessment of the bearing condition was performed, thanks to comparative tests and the use of appropriate equipment from renowned world manufacturers.

The research applied contemporary hardware solutions and modern software packages as reference platforms.

A damage detecting method to rolling bearings based on the measurement of ultrasound emissions enables a more precise assessment of the condition of the bearing. In this way, it is possible to improve and simplify the maintenance processes of rotation equipment, allowing for timely intervention with a significant cost reduction. The application of advanced methods for assessing equipment condition creates preconditions for a significant increase in the reliability of the operation of key facilities in the energy sector, petrochemical and process industries, heating plants and other industries.

Acknowledgments

6 REFERENCES

[1] P. F. Albrecht, R.M. McCoy, E.L. Owen, (1986). "Assessment of the reliability of motors in utility application", IEEE Transactions on Energy Conversion, vol. EC-1, no 1, March 1986, 39-46, DOI:10.1109/TEC.1986.4765668 https://ieeexplore.ieee.org/document/4765668

[2] Tedric A. Harris, (2001). Rolling Bearing Analysis, John Wiley & Sons, INC., 4th edition, ISBN-10: 0-471-35457-0, ISBN-13: 978-0-471-35457-4, 1104 pages

[3] Allan Rienstra, James Hall, (2003). Applying Acoustic Vibration Monitoring to Predictive Maintenance, SDT North America, https://www.maintenanceworld.com/wp-content/uploads/2013/07/ultrasonic.pdf

[4] Hongyu Yang, Joseph Mathew, Lin Ma, (2007). Basis pursuit-based intelligent diagnosis of bearing faults, Journal of Quality in Maintenance Engineering 13(2), DOI:10.1108/13552510710753050, https://www.researchgate.net/publication/27474109_Basis_pursuit-based_intelligent_diagnosis_of_bearing_faults

[5] J. Shiroishi, Y. Li. S. Liang, T. Kurfess, S. Danyluk (1997). Bearing condition diagnosis via vibration and acoustic emission measurements, Mechanical Systems and Signal Processing, Volume 11, Issue 5, September 1997, Pages 693-705, https://doi.org/10.1006/mssp.1997.0113

[6] By Tian Ran Lin, Kun Yu and Jiwen Tan (2017). Condition Monitoring and Fault Diagnosis of Roller Element Bearing, IntechOpen, Bearing Technology, DOI:10.5772/67143, https://www.researchgate.net/publication/317309939_Condition_Monitoring_and_Fault_Diagnosis_of_Roller_Element_Bearing

[7] S. Zhang, S. Zhang, B. Wang, and T. G. Habetler, (2020). Deep learning algorithms for bearing fault diagnostics—A comprehensive review, IEEE Access, vol. 8, pp. 29857–29881, DOI:10.1109/ACCESS.2020.2972859 https://ieeexplore.ieee.org/document/8988271

[8] A. Boudiaf, A. Moussaoui, A. Dahane, and I. Atoui, (2016). A comparative study of various methods of bearing faults diagnosis using the case western reserve university data, Journal of Failure Analysis and Prevention, vol. 16, no. 2, pp. 271–284, Apr. 2016, DOI:10.1007/s11668-016-0080-7, https://link.springer.com/article/10.1007/s11668-016-0080-7

[9] W. Huang, J. Cheng, and Y. Yang, (2019). Rolling bearing fault diagnosis and performance degradation assessment under variable operation conditions based on nuisance attribute projection, Mechanical Systems and Signal Processing, vol. 114, pp. 165–188, Jan. 2019. DOI:10.1016/j.ymssp.2018.05.015 https://www.sciencedirect.com/science/article/pii/S0888327018302553?via%3Dihub

[10] P. Gupta and M. K. Pradhan, (2017). Fault detection analysis in rolling element bearing: A review, Materials Today: Proceedings, vol. 4, no. 2, pp. 2085–2094, DOI:10.1016/j.matpr.2017.02.054, https://www.sciencedirect.com/science/article/pii/S221478531730250X?via%3Dihub

[11] D. H. Pandya, S. H. Upadhyay, and S. P. Harsha, (2013). Fault diagnosis of rolling element bearing with intrinsic mode function of acoustic emission data using APF-KNN, Expert Syst. Appl., vol. 40, no. 10, pp. 4137–4145, Aug. 2013., https://doi.org/10.1016/j.eswa.2013.01.033

[12] Stuart Courtney, (2004). An Introduction to Noise Measurement, SKF Reliability Systems, MB03005, 12 pages, San Diego, CA

[13] Bernard J. Hamrock, Steven R. Schmid, BoO. Jacobson, (2004). Fundamentals of Fluid Film Lubrication, , Marcel Dekker INC, Second Edition, ISBN-10 0824753712 https://doi.org/10.1201/9780203021187

[14] SKF – Product information (2017). Bearing damage and failure analysis, PUB BU/I3 14219/2 EN, June 2017 https://www.skf.com/binaries/pub12/Images/0901d1968064c148-Bearing-failures---14219_2-EN_tcm_12-297619.pdf

[15] Robert M. Jones (2004). Enveloping for Bearing Analysis, SKF Condition Monitoring, San Diego, CA https://www.engr.colostate.edu/~dga/documents/mech307/handouts/bearing_signature_analysis.pdf

[16] SPM Instrument, (2008). The Shock Pulse Method for Determining the Condition of Anti-Friction Bearing, SPM TEC-101 https://ippta.co/wp-content/uploads/2021/01/IPPTA-153-109-113-Condition-Monitoring-of.pdf

[17] ISO - International Organization for Standardization (2014). ISO10816 Mechanical vibration – Evaluation of machine vibration by measurements on non-rotating parts https://www.iso.org/standard/56782.html

Contact information:

Dr Goran ŠINIKOVIĆ, PhD, Associate Professor, (Corresponding author)
University of Belgrade, Faculty of Mechanical Engineering
16 Kraljice Marije Street, 11000 Belgrade, Serbia
E-mail: gsinikovic@mas.bg.ac.rs

Dr Nenad GUBELJAK, PhD, Full Professor
University of Maribor, Faculty of Mechanical Engineering
17 Smetanova Street, 2000 Maribor, Slovenia
E-mail: nenad.gubeljak@um.si

Dr Emil VEG, PhD, Associate Professor
University of Belgrade, Faculty of Mechanical Engineering
16 Kraljice Marije Street, 11000 Belgrade, Serbia
E-mail: eveg@mas.bg.ac.rs

Dr Darko JAGARINEC, PhD, Researcher
University of Maribor, Faculty of Mechanical Engineering
17 Smetanova Street, 2000 Maribor, Slovenia
E-mail: d.jagarinec@gmail.com

Mladen REGODIĆ, MSc, Teaching Assistant
University of Belgrade, Faculty of Mechanical Engineering
16 Kraljice Marije Street, 11000 Belgrade, Serbia
E-mail: mregodic@mas.bg.ac.rs

Ivana MARKOVIĆ, PhD, Assistant Professor
University of Belgrade, Faculty of Mechanical Engineering
16 Kraljice Marije Street, 11000 Belgrade, Serbia
E-mail: imarkovic@mas.bg.ac.rs