# Monitoring rolling bearings – sensor calibration concept based on standards and research

## Monitorowanie łożysk tocznych – koncepcja kalibracji czujników na podstawie norm i badań

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**The article presents a discussion of the importance of analyzing rolling bearing vibrations in industry, emphasizing this parameter as a crucial element in quality control. A review of the literature suggests the need for further advancement in mathematical models and measurement systems, with an increased emphasis on sensor calibration. Although standards such as ISO 15242 regulate the measurement process, they lack detailed specifications for sensor mounting and calibration. The article identifies gaps in the standards regarding precise sensor positioning and calibration, emphasizing the need for further research and development of measurement setups. The proposed studies aim to improve the accuracy and reliability of rolling bearing vibration measurements in industrial practice.**
**KEYWORDS: measurements, calibration, rolling bearings, vibrations**

Artykuł omawia znaczenie analizy drgań łożysk tocznych w przemyśle, wskazując ten parametr jako główny w ocenie jakości. Przegląd badań literaturowych ujawnia potrzebę rozwinięcia modeli matematycznych i systemów pomiarowych, z naciskiem na kalibrację czujników. Normy, takie jak ISO 15242, regulują sposób pomiaru, ale nie precyzują szczegółowych wymagań dotyczących mocowania i kalibracji czujników. Artykuł wskazuje na luki w normach dotyczących precyzyjnego ustawienia i kalibracji czujników, podkreślając potrzebę dalszych badań i rozwoju stanowisk pomiarowych. Proponowane badania mają na celu poprawę dokładności i niezawodności pomiarów drgań łożysk tocznych w praktyce przemysłowej.
SŁOWA KLUCZOWE: pomiary, kalibracja, łożyska toczne, drgania

### Introduction

Vibrations in rolling bearings represent a significant challenge within the industry, with a variety of factors contributing to their occurrence. These include improper lubrication, material wear, and mechanical loads [1, 2]. These oscillations, the result of irregularities in the motion of bearing elements, give rise to vibrations of varying frequencies and amplitudes [3–5]. A comprehensive knowledge of the mechanisms generating these vibrations and the ability to accurately quantify them is essential for guaranteeing the production of high-quality bearings and the effective monitoring of machinery conditions.

This article presents a review of research focused on the analysis of vibrations in rolling bearings. The presentation of these studies offers the chance to become familiar with the various methods of vibration analysis, the results, and the conclusions drawn. This review of the literature is crucial for establishing the relevance of research in the context of design work on sensor measurement systems for sensors utilized in such studies.

A comprehension of the principles of measurement systems employed for the quality control of rolling bearing vibrations is imperative for the accurate interpretation of ongoing work and consideration of the role of sensors in the measurement of vibrations. By elucidating the importance of measurement systems in the context of quality control of rolling bearing vibrations, the article offer valuable guidance to readers who are interested in this subject matter.

The analysis of applicable standards represents a fundamental aspect of quality control. The scientific research and technical standards that have been established provide guidelines regarding the dimensional tolerances, material quality, and testing procedures for these bearings. The article provides a comprehensive analysis of the ISO 15242 standard, which regulates the measurement of vibrations in rolling bearings. The article presents some key issues that are directly related to the measurement system. The recommendations are highlighted and any deficiencies in the available measurement sensors are identified.

The article closes with a discussion of the design of a measurement system for sensors used in the experimental evaluation of rolling bearing vibrations. Key design aspects presented include the selection of appropriate sensors, calibration methods, and methods to minimize measurement errors. In addition, the article considers potential challenges and proposed solutions that may improve the accuracy and reliability of measurements.

### Research review

In the field of studying vibrations in rolling bearings, it is a need to develop comprehensive mathematical models to facilitate a deeper understanding of and more effective diagnosis of their behaviors. At the same time, the development of vibration sensor measurement is crucial to the practical implementation of

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these models, which have the potential to bring significant benefits to the industry.

In article [6], the problem of the lack of comprehensive mathematical models that consider the significant factors affecting the vibration levels of the actual bearings is elucidated. In their review of the literature, the authors identified a notable absence of model bearings, which presents a significant challenge in the calibration of bearing vibration measurement systems. Nevertheless, in article [7], a simplified mathematical model for the analysis of vibrations in rolling bearings with variable stiffness is presented, focusing on two extreme positions of inner ring support. Research on rolling bearing vibrations has resulted in the development of several innovative concepts. One such model describes a new roller bearing configuration that combines the finite element method with a lumped parameter model. This model enables precise simulation of acceleration and stress signals, which can be crucial in fault diagnosis.

In their work [2], Wrzochal et al. highlight the importance of bearing cleanliness in relation to vibration generation, noting the lack of attention to this aspect in numerous theoretical and experimental studies. The objective of future research is to develop a model that predicts the vibrations of newly manufactured bearings under industrial conditions, which is of paramount importance for the bearing industry.

The primary objective of research in the field of measuring vibrations in rolling bearings is the detection of defects related to the components of their construction and the identification of methods for their identification. The authors of the study [9] developed an experimental method for predicting the fatigue life of rolling bearings using modal vibration analysis. Analysis of the impact of defect enlargement on bearing vibrations, as presented in the work of Rathodkar and Jain [10], employs vibration signal analysis techniques. The studies demonstrate that alterations in speed and defect dimensions influence the distribution and amplitude of frequencies, which can be crucial for diagnosis and repairs in rotor-bearing systems. As a result of technological advances, research on improving fault recognition through vibration analysis and machine learning has become increasingly prevalent.

In their article, Khaire and Phalle [11] present a methodology for monitoring the condition of a ball bearing, which uses vibration analysis and machine learning for the effective diagnosis of internal ring faults. The results of their research demonstrated that the proposed model, which integrates these techniques, achieves high accuracy in identifying faults, suggesting its potential for application in industrial practice. It is also noteworthy that research has been conducted using the finite element method (FEM) in the context of rolling bearings. In the study [12], the authors focused on developing an angular contact ball bearing and its experimental verification in load-control spindle systems with load control.

The accuracy of signal analysis is of critical importance in the quality control of rolling bearings, as it allows for an exact evaluation of their technical condition. A comprehensive analysis of vibration and acoustic characteristics allows the identification of even minor deviations from optimal performance, ensuring the production of top-quality products and reducing the risks associated with mechanical failures. The most commonly utilized analytical techniques include the wavelet transform, the fast Fourier transform (FFT), and automatic data processing.

In the article [13], a comprehensive analysis of vibration measurement methods was conducted in rolling bearings, considering different stages of their life cycle. By classifying these methods and identifying their associated limitations, researchers underscore the significance of selecting appropriate measurement techniques for an accurate assessment of the condition of these components. In addition, the article elucidates not only the importance of measurements to detect damage, but also the design aspects that may influence the occurrence of vibrations in rolling bearings.

It is imperative that theoretical studies on vibration measurement systems for rolling bearings be complemented by experimental results. In their analysis of structural solutions in devices to test rolling bearing vibrations, Wrzochal [14] identifies the advantages and disadvantages of individual components and demonstrates the importance of reliable comparative tests. The article compares traditional and modern measurement methods, evaluating their accuracy and effectiveness in the context of the impact of vibrations on the quality of machinery and mechanical devices. The authors highlight that the precision of the measurements depends on the frequency of vibrations and the type of measuring equipment used.

In the study [16], a comparative analysis of selected measurement systems was performed. The requirement for further research involving a larger sample of bearings of various types and sizes, as well as the importance of establishing a reference system for precise vibration measurement was indicated.

In their study, Adamczak and his team [17] described the research methodology and the Anderon STPPD test stand, which was designed to assess the vibration levels of the rolling bearings. Comparative studies were conducted with the SKF MVH900 device, which suggested that the Anderon STPPD could be an effective alternative to the more expensive equipment currently available on the market. The article presents an innovative approach to evaluating measurement systems for industrial rolling bearing vibrations, with a particular emphasis on the accuracy assessment of three different measurement systems and the identification of factors influencing their precision. The utilization of a laser Doppler vibrometer as a reference point enabled for a comprehensive investigation of measurement precision. Piotrowicz and Adamczak [19] developed an innovative measurement system to evaluate the vibrations generated by ball bearings, to examine the consistency of the results with a reference system, and assess the accuracy of the measurement across an array of frequency ranges.

The analysis indicates that systems for testing the vibrations of rolling bearings require additional setup to calibrate the vibration sensors to guarantee their precision and reliability. Sensor calibration is of critical importance for the elimination of measurement errors and the facilitation of more precise monitoring of the technical condition of bearings. Calibration ensures consistency and comparability of measurement results, which is essential for assessing the quality and durability of rolling bearings. Furthermore, regular calibrations can detect and correct sensor drifts, preventing potential failures and machine downtime. The implementation of such calibration sets will contribute to the advancement of research standards and the enhancement of the effectiveness of vibration diagnostics for rolling bearings.

## Standard guidelines

In ISO 15242, the assessment of structural vibrations in a rotating rolling bearing is conducted by mounting a sensor (which may be displacement, velocity, acceleration, or even force sensors) at a designated location on one of the bearing rings or a mechanical component of the test rig. It is imperative that the direction of action, either axial or radial, be specified in relation to the reference frame. The bearing is rotated at a specified speed with a defined load, and the signal from the sensor is recorded for a specified period. The collected data are analyzed to calculate the parameters that characterize the vibrations. The results obtained convey information about the vibrations experienced by the bearing under the specified measurement conditions.

Vibration measurements of bearings should be conducted with a stationary outer ring and a rotating inner ring at a specified rotational frequency, contingent on the bearing's dimensions and design. Alternatively, vibrations can be measured with a stationary inner ring and a rotating outer ring. During the observation period, the actual rotational frequency must not exceed the nominal rotational frequency by more than 1% and not be lower than it by more than 2%.

To guarantee exact kinematic conditions, it is essential to load the bearings during vibration measurement. The load should be of sufficient magnitude to prevent the rolling elements from slipping relative to the raceways of the inner and outer rings, yet it should not impact the measurement outcomes.

### *Requirements for sensor*

A transducer is a device that converts mechanical motion into an electrical signal, expressed in units of displacement, velocity, or acceleration. In the case of a contact transducer, it is of the utmost importance to ensure that the device does not interfere with the vibrations of the ring. The contact must be sufficiently strong to detect all vibrations within the appropriate frequency range. To achieve this, it is necessary to ensure that the moving masses of the transducer are as small as possible. Furthermore, if vibrations are transmitted through the transducer's tip that contacts the ring, it is essential to consider the potential for contact resonance.

It is optimal to present signals in terms of velocity, as this provides the most precise resolution across a wide frequency range. The oscillatory motion of the ring is a complex superposition of displacements with varying amplitudes and frequencies. While high amplitudes may occur at higher frequencies (particularly in defective bearings), amplitudes generally decrease with increasing frequency, reaching the nanometer range at several kilohertz.

### *Measurement methods*

- **Method of time-averaging.** The velocity signal in each frequency band shall be measured and the resulting value averaged over a period of at least 0.5 seconds at 1,800 RPM, once the vibration readings have stabilized. The readings should exhibit only occasional, random fluctuations around the mean. The minimum averaging time is inversely proportional to the spindle's rotational frequency. The accuracy of the effective value (RMS) detector should be within ±5% of the reading for signals with a crest factor of up to five.
- **Measurement sequence.** Measurements must be conducted at a specified number of positions. For a bearing to be classified as acceptable, the highest vibration reading within the appropriate frequency range must fall within the limits that have been previously established by the manufacturer and the customer.

## Aspects not specified or overlooked by the standard in the context of vibration measurement sensors for rolling bearings

### *Sensor positioning and mounting*

The standard does not indicate the methodology for mounting the sensor to the measurement system. As outlined in the article by Wrzochal [16], various manufacturers of bearing vibration analysis setups have proposed their own solutions. Most designs assume an oval external shape for the sensor housing, which requires the use of a clamping sleeve-based solution.

Another issue is related to the point of application of the sensor. While the document provides an approximate positioning, this depends on the bearing manufacturer. The standard also defines the perpendicularity error of the sensor probe relative to the bearing axis, which must not exceed 5°. In Fig. 1 it is illustrated the assumed sensor application position. Additionally, the standard considers the axial positioning error based on the outer diameter:

$D \leq 70$ mm – 0,5 mm

$D > 70$ mm – 1 mm

Furthermore, there is a dearth of information pertaining to the range of contact force applied by the sensor's measurement probe. Each sensor possesses its preload and the pressure it generates has the

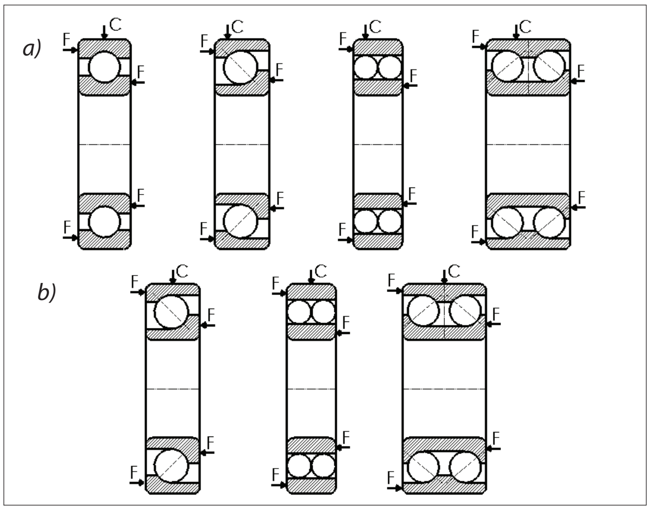


Fig. 1. (*a*) Standard sensor positioning diagram; (*b*) alternative position excluding single-row ball bearings; *C* – sensor probe application point; *F* – force application point

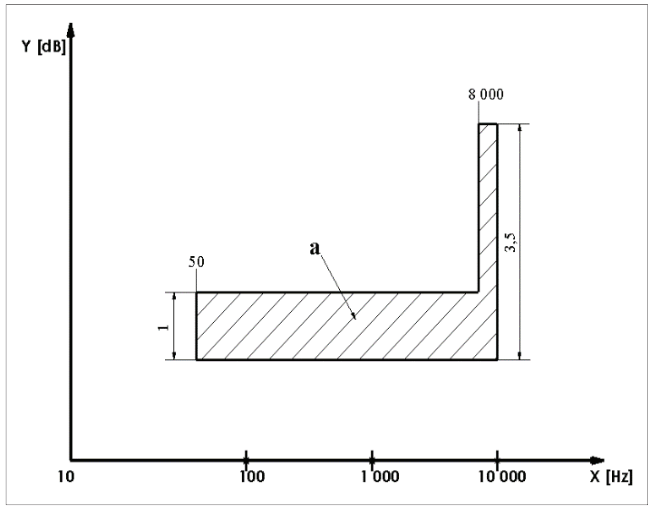


Fig. 2. Frequency response acceptability limits chart (*a* – acceptable zone)

potential to significantly affect the measurement results. This issue is only addressed in "Annex A" with the statement: *When a contact type transducer is used, care shall be taken to ensure that the transducer does not influence the vibrations of the measured ring.* However, this statement is vague and lacks sufficient detail.

"Annex A" of the ISO 15242 standard elucidates the significance of contact force and resonance in the context of vibration measurements of rolling bearings using contact methods. Contact resonance arises due to the sensor tip's behaviour as a spring, characterized by the modulus of elasticity *E*. "Annex A" incorporates a frequency table for varying contact surface ring diameters of sensors.

*Calibration and measurement data*

The ISO 15242 standard outlines the following specifications:

- It is essential that the transducer be calibrated for both sensitivity and amplitude linearity.
- The transducer's response to different frequencies should be checked.
- It is imperative that the transducer is correctly configured and positioned in accordance with the specified requirements during the measurement process.

However, none of the aforementioned recommendations are specified in sufficient detail. This is another reason for the need to develop specific requirements for sensors used in measurements. Additional information obtained from the standard includes details about the transducer signal. The standard physical quantity for measurement is the root mean square (RMS) velocity of vibrations ($v_{rms}$), expressed in micrometres per second (µm/s). The measurement direction can be radial or axial, depending on the type of bearing.

The velocity signal should be subjected to analysis in one or more frequency bands. The range of these bands is contingent upon the spindle's rotational frequency. For a rotational frequency of 30 Hz (1,800 RPM), the frequency range is from 50 Hz to 10,000 Hz. The precise frequency ranges are delineated in other sections of the ISO 15242 standard. It is imperative that the transducer's frequency response falls within the boundaries delineated in Fig. 2.

Furthermore, the standard indicates that in the event of a discrepancy between the specified frequency range of 50 to 10,000 Hz, the acceptability zone of the sensor's response must be adjusted proportionally. An illustrative example is provided in the table.

**TABLE. Example of Proportional Adjustment of Sensor Response Acceptability Zone**

| Rotation speed | Frequence |
|---|---|
| 900 1/s | to 5 000 Hz |
| 3600 1/s | to 20 000 Hz |

The minimum requirements for the transducer's response, as illustrated in Fig. 2, must be calibrated to account for the compensated output signal of the amplifier. The permissible deviation from linearity should not exceed 10% for vibration amplitudes within the velocity range of 10 µm/s to 3,000 µm/s across the entire frequency range. The sensitivity of the transducer, in combination with signal conditioning, should be specified with an accuracy of ±5%.

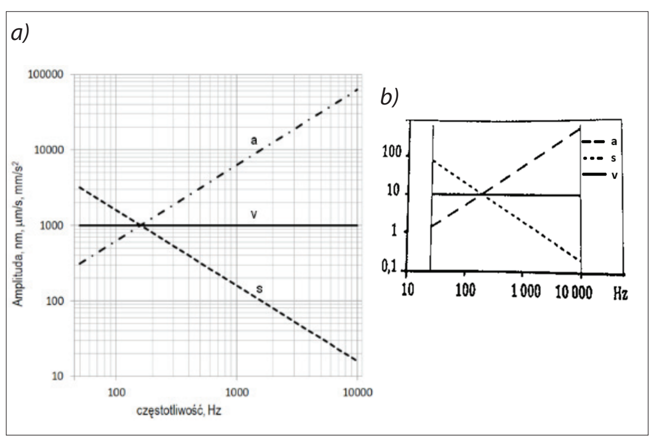


Fig. 3. Amplitude dependencies for constant vibration velocity: *a*) 1000 µm/s – PSv3 sensor; *b*) 10 µm/s – ISO 15242 Example

Another issue addressed by the standard is the relatively wide range of generated amplitudes. There is no specification regarding the type of excitations, measurement method, or the number of measurement points (which generate different amplitudes). In Fig. 3 there is a graph of the electrodynamic sensor designed by the Kielce University of Technology, as well as a graph from the ISO 15242 standard. These graphs illustrate the proportional relationship between signal dependencies in the context of generating various amplitudes.

*Conclusion*

The ongoing work is focused on the development of a measurement setup for sensors that will be used in the experimental evaluation of rolling bearing vibrations. At present, there are no specific requirements for calibrating measurement sensors or detailed information on the construction of such setups. This article demonstrates the essentiality of developing a dedicated measurement setup, highlighting significant deficiencies in existing standards. The presented research indicates the need for further work to ensure precise and reliable vibration measurements.

The key factors that affect measurement uncertainties have been identified, including signal processing precision and the resistance of the sensor to environmental conditions. The subsequent article will present detailed design solutions for the proposed measurement setup, based on the conclusions and research discussed in this work. This will represent the next step in optimizing these technologies, namely by identifying, evaluating, and minimizing the identified uncertainties. The aim is to improve the accuracy and reliability of measurement systems.

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