

System for the Assessment of the Dynamic State of Ball Bearings with Respect to Vibration They Generate

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ABSTRACT

Bearings are important components of many structures. Their reliability is a prerequisite for the correct operation of designed and operated equipment. This is why bearing manufacturers want to produce bearings with greater load-carrying capacity, durability and bearings that generate as little vibration as possible. In the paper, a newly developed device for measurements of the level of vibrations produced by ball bearings was described. Basic requirements for such devices, their suitability for the bearing industry applications, and the mechanical construction of the most important units were discussed.

Keywords: rolling bearing, bearing vibration, vibration, measurement.

INTRODUCTION

Bearings constitute basic elements in many mechanical devices. Bearings are responsible for the rotation of the mating parts (shafts and other rotating components), they support these components and reduce the force required to perform a rotary motion by taking over radial and/or axial loads. The main components of a bearing include the outer ring (fixed in the housing), the inner ring (in the bore of which, the rotating shaft is fixed), the rolling elements (balls, rollers, needles) and the cage that supports the rolling elements.

The basic criteria [1], decisive for the selection of a rolling bearing, include the following: the structural constraints in the device design and the dimensional limitations of the bearings, magnitude and direction of the load, the rigidity of the support of rotating elements, the speed of rotation, the load bearing capacity, the possibility of coaxiality error reduction, the accuracy of manufacture, and quiet running behaviour, i.e., the level of vibration produced. Currently, bearing quietness, that is the level of vibration it produces, is one of the most important parameters in

the assessment of bearing quality. By determining the level of vibration produced by a bearing, it is possible to identify the type of defect in the bearing, the site at which it originated, the properties of the lubricant, and contamination in the bearing.

To measure vibrations in bearings, specialist measurement instruments are employed. They must satisfy the requirements specified in standards [2, 3, 4]. When tested, the bearing sits on a measurement spindle, which rotates at 1800 rpm. This is the basic rotational speed used in measurements of bearing vibration. In measurements, the rotational speed should not exceed the nominal value by more than 1%, or be lower by 2%. Other values of rotational speed are also allowed, namely 700 rpm, 900 rpm, or 3600 rpm. The bearing manufacturer can measure the vibration level produced by bearings at other rotational speeds only if that is required by the client. The inner ring of the bearing rotates with the spindle, whereas the outer ring of the bearing is restrained by axial pressure. The value of the clamping force depends on the size of the bearing tested and should remain stable throughout the measurement. The pressure must be applied coaxially and it must be

uniformly distributed on the face of the bearing outer ring. The signal measurement time should be not lower than 0.5 s. The measurement should be taken after the readings have stabilised. Random factors can produce variation in results. For that reason, the effect produced by unstable dynamic state of the rolling bearing should be limited as much as possible. The pressure tips in the axial pressure are alterable and can be adjusted to the bearing under test. Measurements of vibration of a rolling bearing mounted on a measurement spindle and restrained by the axial pressure are taken using a specialist electrodynamic vibration velocity sensor. The sensor is mounted on the measurement clamp, adjustable in two axes, and the measuring tip is in contact with the stationary outer ring of the bearing of concern, at its mid-height. The resulting measurement signal is analysed in three frequency ranges: low range 50–300 Hz, medium range 300–1800 Hz, and high range 1800–10000 Hz.

Fast Fourier Transform (FFT) [5, 6] or Wavelet Transform (WT) [7] were used to analyse vibration produced by bearings. These methods analyse individual components or the time wave forms bands. The waveform characteristic elements are related to the design parameters of the rolling bearings, which makes it possible to determine the faults in the bearings. When the basic design parameters of the rolling bearings and their rotational speed are known, the frequencies of the faulty bearing components can be calculated [8]:

- Rotational frequency of the inner ring:

$$f_w = p_w \quad (1)$$

- Ball Pass Frequency Outer (BPFO):

$$f_{pz} = \frac{z}{2} \cdot p_w \cdot \left(1 - \frac{d}{D_m} \cdot \cos \alpha\right) \quad (2)$$

- Ball Pass Frequency Inner (BPFI):

$$f_{pw} = \frac{z}{2} \cdot p_w \cdot \left(1 + \frac{d}{D_m} \cdot \cos \alpha\right) \quad (3)$$

- Ball Spin Frequency (BSF):

$$f_{ET} = \frac{d_m}{2D_0} \cdot p_w \cdot \left[1 - \left(\frac{d}{D_m} \cdot \cos \alpha\right)^2\right] \quad (4)$$

- Fundamental Train Frequency (FTF):

$$f_K = \frac{1}{2} \cdot p_w \cdot \left(1 - \frac{d}{D_m} \cdot \cos \alpha\right) \quad (5)$$

where: z – number of rolling elements, p_w – rotational speed of bearing-mounted shaft, d – diameter of rolling elements, D_m – pitch diameter of the bearing, α – contact angle of rolling bearing.

A wide spectrum of vibration frequencies generated by the bearing makes it possible to identify defects in the bearing of concern. In the low frequency range, it is possible to detect outer raceway defects, or roundness deviations. In the medium frequency range, inner raceway defects, ball damage and waviness errors of the mating surfaces can be identified [9, 10]. In the high frequency range, it is possible to diagnose inadequate lubrication, bearing contamination, or inappropriate roughness of the raceway or a ball [11]. Each frequency range detects different defects or faults present in the bearings and each frequency range is important. Methods for evaluating the technical condition of bearings and their diagnosis are being used by many scientific institutions nationally and internationally. In addition, the vibration measurement system described below has promisingly been used to detect bearing defects [12, 13].

METHODOLOGY OF MEASUREMENTS

The MDL-54 device was developed for measurements of rolling bearing vibration level (Fig. 1). The construction was preceded by the analysis of the design options concerning vibration level measurement instruments. The analysis covered devices manufactured in different



Fig. 1. MDL-54 device for measurements of ball bearing vibration levels

countries by both major and smaller companies. The operation principles and the requirements for devices of this type were also taken into account. In this paper, the most important units of the device are described.

Hydrodynamic spindle with a measurement head

The spindle is the basic unit in the bearing vibration measurement device. Here, it is a hydrodynamic spindle (Fig. 2), constructed by FŁT Krašnik S.A. engineers. The spindle, driven by low-pressure oil, allows precise rotation of the tested bearing. On one side (the operator's side), the spindle is equipped with a coned seat, used to accommodate an interchangeable measuring mandrel. The other side is designed to transfer the rotational drive. The mandrels are constructed individually to fit the type of bearing being tested test. The spindle seat and the mandrel must be able to produce minimum measurement errors.

The measurement head, together with a vibration sensor, is mounted on the spindle body. The measurement head is capable of precise positioning the sensor in two axes so that the sensor would

be in contact with the bearing of concern. Additionally, the head is equipped with a mechanism used to raise or lower the measurement sensor. The bearing is raised while it is being slid onto the rotary mandrel, whereas during the measurement, the sensor is lowered onto the bearing.

Axial pressure unit

The patent-protected [14] ball bearing clamp (Fig. 3) provides axial, stable, elastic clamping. The clamping force and its stability are ensured by an electric actuator, which can be smoothly adjusted depending on the bearing size. Articulated three-point clamping and pressure tips covered with vulcanised rubber guarantee stable force application over the entire bearing circumference. The clamping device is equipped with a special mechanism that prevents the pressure tips from being rotated and cut. Additionally, the axial pressure unit has a pocket container to hold bearings to be tested. The operator puts the bearing to be tested into the pocket, then he initiates the measurement, and finally removes the bearing from the pocket when the measurement has been completed.

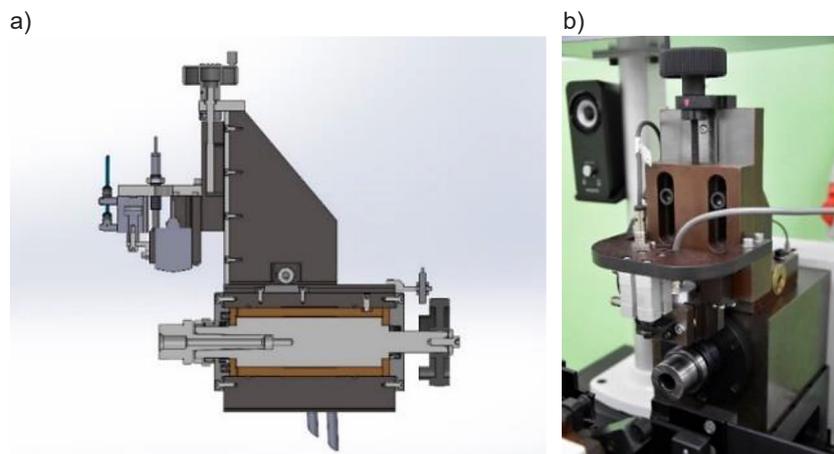


Fig. 2. Hydrodynamic spindle with the measurement head: a) design; b) actual view

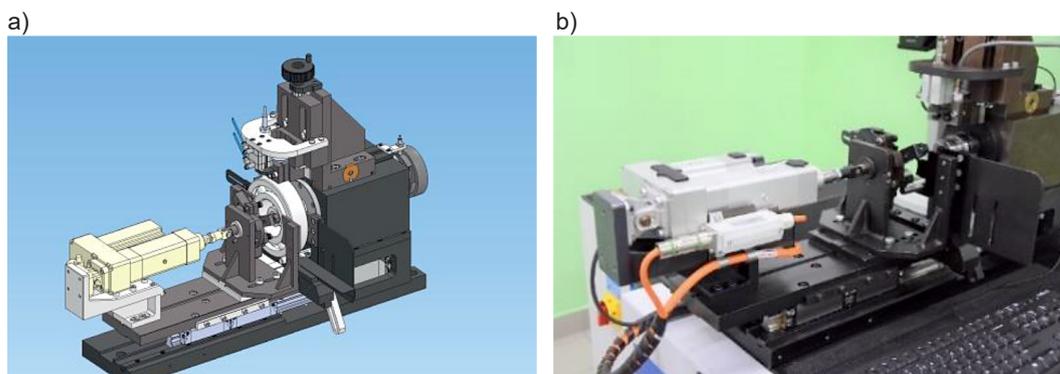


Fig. 3. Axial pressure unit in the device for vibration level measurements: a) design; b) actual view

Vibration sensor

The operation principle of the sensor (Fig. 4) is based on the current induction in the coil vibrating in the magnetic field. The coil can move freely in the magnetic field at the frequency and amplitude forced by the vibrating bearing. The lightweight coil, having an appropriate number of windings, generates a high-frequency signal. Due to special springs, the carcass remains in continuous contact with the tested bearing, while force value remains constant. A magnetic circuit provides constant, strong enough magnetic field in the area where the carcass-wound coil moves. The two coaxially connected units are prevented from rubbing against each other. The sensor signal is processed and analysed in three frequency ranges: low (50–300 Hz), medium (300–1800 Hz) and high (1800–10000 Hz). Such a task is best served by the measurement of vibration velocity, which behaves most stably in the most relevant frequency range for measurement. Velocity sensors are not free from defects. They have a complex design, are expensive and sensitive to damage. For this reason, they are not used in the monitoring on-line of machinery and equipment. They do, however, perform excellently in bearing quality control equipment. For this reason, research and development studies are already underway that will lead to their minimisation.

Spindle drive

The hydrodynamic spindle (Fig. 5) is driven by a motor with special bearings, controlled

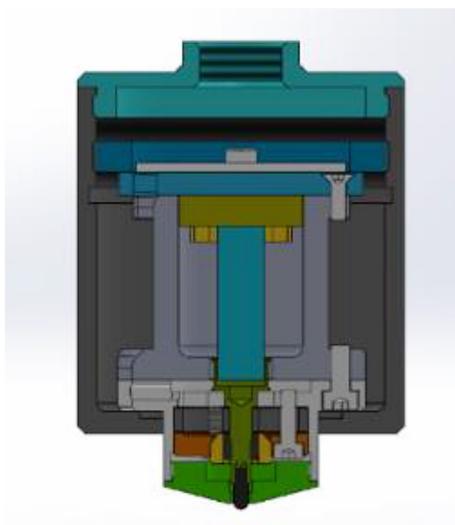


Fig. 4. Vibration sensor

by a servo-drive. The spindle revolutions are controlled by a sensor. The signal from the sensor is transmitted to the controller, which keeps constant rotational speed at 1800 rpm ($\pm 1\%$) for the ball bearings and 900 rpm ($\pm 1\%$) for tapered roller bearings. The motor sits on a cushioned plate. The drive is transmitted by belts designed for such applications.

Vibration attenuating elements

The unit support structure is suitable for both applications. The structure consists of two frames, the supporting one and the upper one, which are made of steel profiles (Fig. 6). The lower support frame is equipped with dampers to attenuate external vibration. The role of additional dampers,

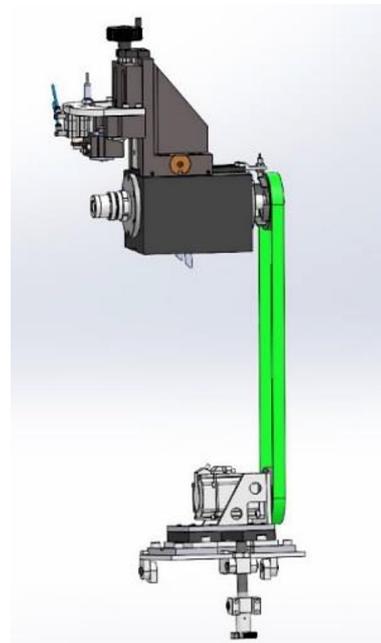


Fig. 5. Spindle drive



Fig. 6. Frame unit with dampers

positioned between the frames, is to attenuate internal vibrations. The main plate, connected to the upper frame, is made of spheroidal graphite cast iron, which has vibration-damping properties. The bodies of the spindle and measurement head are also made of spheroidal graphite cast iron.

The device control

The task of the universal software tool for the measurements of vibration produced by ball and tapered roller bearings is to collect the signals from the vibration sensor, analyse them and control the movements of all units.

The measurement path (Fig. 7) includes a vibration sensor (inductive speed sensor), a measurement amplifier, and an analogue-to-digital converter. The communication between computer and the measurement rig proceeds via a PLC with the use of RS232 serial port. To analyse the signal, information on the speed of the bearing under test is required (1800 rpm for ball bearings and 900 rpm for tapered roller bearings). For individual customer requirements, it is possible to measure bearing vibration levels at other speed settings.

The numerical data stream is subjected to Fast Fourier Transform (FFT) analysis on continuous basis (Fig. 8c, d), which makes it possible to constantly monitor the noise spectrum. Based on the spectrum, the RMS values of the noise in the individual frequency ranges are determined: lower (50–300 Hz), medium (300–1800 Hz) and upper (1800–10000 Hz). The sampling rate of 25 600 Hz was used to observe the noise time course and to perform Fast Fourier Transform analysis in real time. For spectrum observations on current basis, the FFT algorithm was employed. When

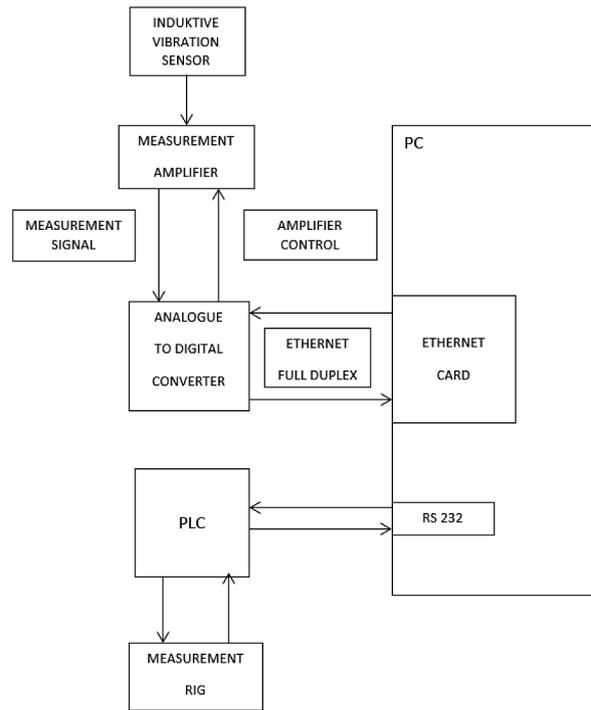


Fig. 7. Block diagram of the measurement path

analysing the recorded signal, the spectrum is determined based on the number of samples at a recording time of 2.5 s.

Exemplary screenshots of the software employed for the analysis of vibration level generated by rolling bearings are shown in Figure 8.

The software is still being improved. The measurement results are given in the form of basic parameters used when evaluating bearing vibrations: amplitude (µm), velocity (µm/s) and acceleration (µm/s²). Optionally, measurement results can be also presented by means of special parameters such as Anderson, %FAG and Velocity Level (VL).

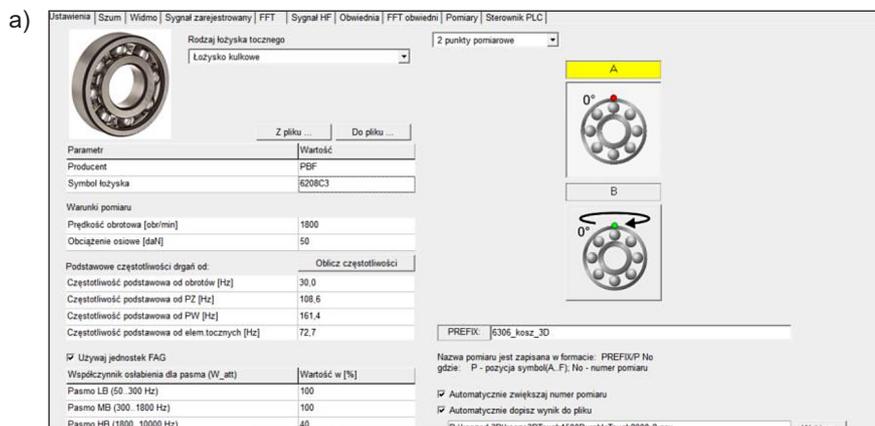


Fig. 8. Screenshots: a) settings

The above-mentioned are special, individual parameters, which clients sometimes require from bearing manufacturers. Those parameters are defined as follows.

Parameter Anderson is defined by dependence (6).

- Anderson (*And*)

$$V_A = \frac{V_{um}}{0,0254 \cdot 2\pi \cdot 30 \sqrt{\log_2 \frac{f_t}{f_b}}} \quad (6)$$

where: V_A – measured value of vibration level in Andersons, V_{um} – measured value of vibration level in $\mu\text{m/s}$, f_t – upper frequency limit of the measurement range, f_b – lower frequency limit of the measurement range.

Parameter %FAG is determined from formula (7).

- %FAG (%)

$$V_{\%FAG} = \frac{V_A}{W_R \cdot W} \cdot 100\% \quad (7)$$

where: $V_{\%FAG}$ – percentage value of measured vibration level, V_A – measured value of vibration level in Andersons, W_R – attenuation factor for a given bearing type, chosen individually for each frequency range, W – factor chosen individually for each frequency range.

The velocity level (V_L) parameter is determined on the basis of formula (8).

- V_L – vibration measurement in decibels (dB)

$$V_L = 20 \log \left(\frac{qV_{RMS}}{qV_{RMS0}} \right) \quad (8)$$

where: qV_{RMS} – measured value of vibration velocity of a rolling bearing under test, qV_{RMS0} – measured value of vibration velocity of a reference bearing.

THE MEASUREMENT RESULTS

The MDL-54 test rig was examined for operational correctness. To this end, comparative tests on 6208 ball bearing were conducted. The SKF MVH-200C tester, which is used in the FLT Krašnik S.A. laboratory, provided the reference system. Statistical analysis of the measurement data was carried out to verify of the correctness of the results. The measurements were taken in two stages. The first stage involved a series of 51 vibration measurements for a single bearing, which made it possible to determine basic parameters,

such as the arithmetic mean, the Root Mean Square Deviation of a single measurement, or the range.

However, to check the MDL-54 rig applicability to industrial measurements, the device was examined under manufacturing conditions by randomly selecting 51 rolling bearings of 6208 type. To evaluate the measurements, the method taking into account variable error of measurement, reported in the literature [15], was applied.

Additionally, a correlation coefficient between the results obtained for the devices compared was determined.

The method accuracy is expressed by formula (9).

$$DP = |\bar{w}_{\Delta Z} \pm k_p s|_{max} \quad (9)$$

where: k_p – coefficient of expansion ($p = 0.95$) obtained from normal distribution tables, s – standard deviation of relative measurement error, $\bar{w}_{\Delta Z}$ – mean experimental relative measurement error for comparable instruments.

However, the relative error for each measurement being compared was determined based on formula (10). In comparative investigations, a traditional parameter concerning vibration velocity ($\mu\text{m/s}$) was employed.

$$\bar{w}_{\Delta Z} = \frac{\Delta Z_p - \Delta Z_a}{\Delta Z_a} \quad (10)$$

where: ΔZ_p – vibration measured value for a given frequency range, obtained to take measurements of the MDL-54 system, ΔZ_a – vibration measured value for the same frequency range, obtained to take measurements of the SKF MVG-200C reference system.

Statistical tools are used to determine individual distribution characteristics of the measurement series for each measurement system. Additionally, those tools make it possible to carry out comparative tests, such as arithmetic mean or variance, concerning the most important parameters of the distributions.

The test of comparison of mean values from two populations is based on the choice of one out of two hypotheses. The null hypothesis H_0 states that there is no reason to claim that the arithmetic means from two measurement series differ significantly from each other (the difference in errors is random). Conversely, the alternative hypothesis H_1 states that the means from two series differ significantly from each other, which indicates

a systematic error. The choice of hypothesis is made by comparing the obtained U value with the U_{kr} value selected based on the probability level assumed in the normal distribution tables. If $U < U_{kr}$, H_0 is true, whereas if $U \geq U_{kr}$, H_1 is chosen.

The test of comparison of variances from two populations with normal distributions is based

on the choice of one out of two hypotheses. The null hypothesis H_0 states that there is no reason to claim that the variances of two measurement series differ significantly from each other (the difference in errors is random). Conversely, the alternative hypothesis H_1 states that variances of two series differ significantly from each other,

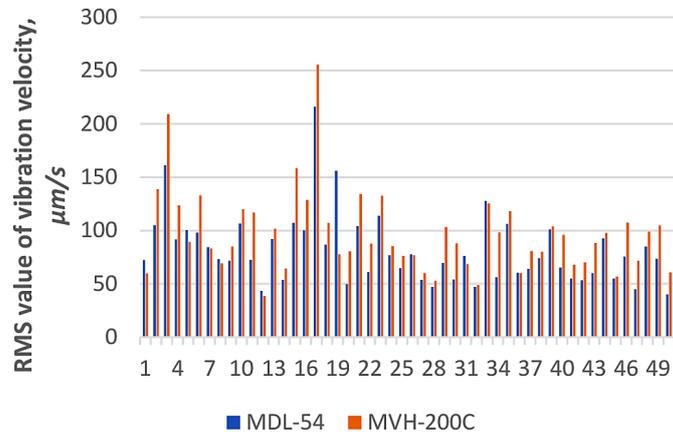


Fig. 9. Bar graph of bearing series measurements obtained with the tested and reference systems in the low frequency range 50–300 Hz

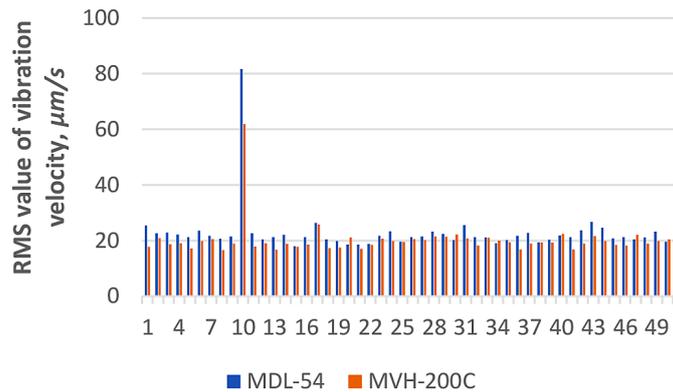


Fig. 10. Bar graph of bearing series measurements obtained with the tested and reference systems in the medium frequency range 300–1800 Hz

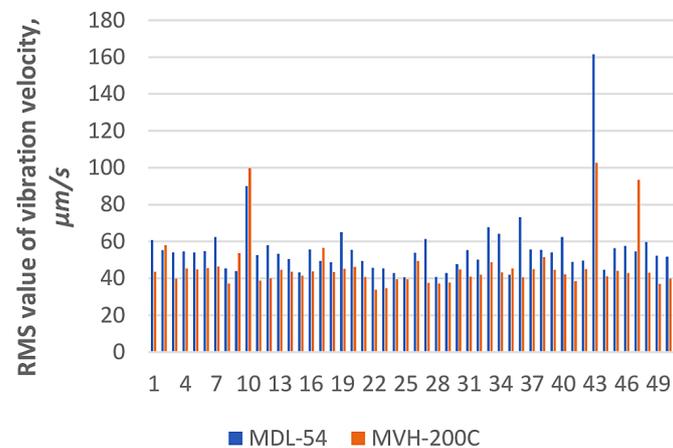


Fig. 11. Bar graph of bearing series measurements obtained with the tested and reference systems in the high frequency range 1800–10000 Hz

which indicates a systematic error. The choice of hypothesis is made by comparing the obtained value of F-statistic with the F_{kr} value found from Fisher-Snedecor tables. That is based on the assumed probability level and the number of degrees of freedom resulting from the number of measurements in each series. If $F < F_{kr}$, H_0 is true, whereas if $F \geq F_{kr}$, hypothesis H_1 is chosen.

The measurement results are divided into three groups corresponding to three frequency ranges under consideration.

Figures 9, 10, and 11 illustrate the second stage of investigations, namely measurements taken for 51 bearings in two arrangements. In the first arrangement, the MDL-54 system was tested, and in the other arrangement, the MVH-200C reference system was used.

The results of the analyses are shown in Tables 1–3. The statistical results, including the relative error for each frequency range, are listed. The results obtained from statistical analyses provided the basis for the conclusions.

Table 1. The comparative analysis results for the 50–300 Hz frequency range

Measurement system	MDL-54	MVG-200C
Sample size of measurements	51	
Arithmetic mean, $\mu\text{m/s}$	62.86	75.23
Root Mean Square Error of a single measurement, $\mu\text{m/s}$	6.11	6.19
Minimum value, $\mu\text{m/s}$	48.8	52.7
Maximum value, $\mu\text{m/s}$	73.8	93.7
Range, $\mu\text{m/s}$	25.0	41.0
Final result of a single measurement, $\mu\text{m/s}$ ($p = 0.95$)	62.86±11.98	75.23±12.14
Test for comparison of means, U-statistic; U_{kr}	-1.23; 1.96	
Test of comparison of variances, F-statistic; F_{kr}	1.01; 1.6	
Pearson correlation coefficient	0.84	
Accuracy of the analysed methods DP, %	57.35%	

Table 2. The comparative analysis results for the 300–1800 Hz frequency range

Measurement system	MDL-54	MVG-200C
Sample size of measurements	51	
Arithmetic mean, $\mu\text{m/s}$	26.37	23.17
Root Mean Square Error of a single measurement, $\mu\text{m/s}$	1.9	1.61
Minimum value, $\mu\text{m/s}$	21.2	19.8
Maximum value, $\mu\text{m/s}$	30.0	29.7
Range, $\mu\text{m/s}$	8.8	9.9
Final result of a single measurement, $\mu\text{m/s}$ ($p = 0.95$)	26.37±3.71	23.17±3.14
Test for comparison of means, U-statistic; U_{kr}	0.79; 1.96	
Test of comparison of variances, F-statistic; F_{kr}	1.39; 1.6	
Pearson correlation coefficient	0.96	
Accuracy of the analysed methods DP, %	35.13%	

Table 3. The comparative analysis results for the 1800–10000 Hz frequency range

Measurement system	MDL-54	MVG-200C
Sample size of measurements	51	
Arithmetic mean, $\mu\text{m/s}$	43.52	55.33
Root Mean Square Error of a single measurement, $\mu\text{m/s}$	2.50	4.75
Minimum value, $\mu\text{m/s}$	38.7	47.9
Maximum value, $\mu\text{m/s}$	50.7	66.8
Range, $\mu\text{m/s}$	12.0	18.9
Final result of a single measurement, $\mu\text{m/s}$ ($p = 0.95$)	43.52±4.88	55.33±9.26
Test for comparison of means, U-statistic; U_{kr}	-1.37; 1.96	
Test of comparison of variances, F-statistic; F_{kr}	3.59; 1.6	
Pearson correlation coefficient	0.70	
Accuracy of the analysed methods DP, %	64.13%	

CONCLUSIONS

Based on the investigations reported above, the following conclusions can be drawn:

1. The arithmetic means obtained in the investigations are close. In the medium frequency range, the arithmetic means are very close to each other and do not differ in a significant way (the difference results from random errors). However, in two other frequency ranges, namely low and high, the differences are greater, but generally the situation is similar to that in the medium frequency range. This means that the readings of the newly designed measuring device are congruent with the readings provided by the reference system.
2. The variance comparison test showed that in the two frequency ranges (low and medium), the difference in the variances obtained is negligible. In the high frequency range, however, a major variance difference is found. That may indicate the occurrence of a considerable systematic error.
3. The Pearson correlation coefficient computed for the results in all frequency ranges is positive and very strong.
4. The accuracy DP of measurement methods for the medium frequency range amounts to 35%. In the low and high frequency ranges, the accuracies are close to each other and they fluctuate around $60 \pm 4\%$. The measurement results were affected by many time-varying factors that are dynamic in nature. Consequently, an accuracy of 60% is acceptable. The accuracy of dynamic measurement systems that amounts to 50% should be considered very good, while DP ranging 50–70% makes it possible for the device to be conditionally accepted for measuring bearing vibration levels. If the measurement accuracy exceeds 100%, the reasons for the occurrence of such a high dynamic state should be carefully analysed. Precise determination of the accuracy limits in dynamic systems will be possible after conducting further investigations and tests.

In order to find out what caused discrepancies in the results, the following steps should be taken:

- to carry out investigations into a larger number of measurement systems;
- to examine the impact of differences in the design of measurement systems, and to assess

the possibility of making adjustments to minimise their effect on the measurement results;

- to choose the best reference system for comparative investigations and to determine possible correction factors for comparable measurement rigs;
- to develop a reference measurement system that could serve as a benchmark for other measurement devices;
- to specify reference ball bearings for the calibration of measurement rigs;
- to carry out similar statistical tests, taking into account measurement error, for other parameters including amplitude (μm), acceleration ($\mu\text{m/s}^2$), Anderon (And), %FAG (%), and V_L (dB).

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